Report of the
Defense Science Board
Task Force

on

Wideband Radio Frequency Modulation

Dynamic Access to Mobile Information Networks

July 2003

Office of the Under Secretary of Defense
for Acquisition, Technology, and Logistics
Washington, D.C. 20301-3140

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 2003

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Wideband Radio Frequency Modulation: Dynamic Access to Mobile Information Networks

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Defense Science Board
Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)
3140 Defense Pentagon
Room 3D865
Washington, DC 20301-3140

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Science Board
Office of the Under Secretary of Defense (Acquisition, Technology & Logistics)
3140 Defense Pentagon
Room 3D865
Washington, DC 20301-3140

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
A: Unlimited Distribution

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES
110

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLAS	UNCLAS	UNCLAS	N/A

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

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3140 DEFENSE PENTAGON
WASHINGTON, DC 20301-3140

DEFENSE SCIENCE BOARD

JUL 30 2003

MEMORANDUM FOR ACTING UNDER SECRETARY OF DEFENSE
(ACQUISITION, TECHNOLOGY & LOGISTICS)

SUBJECT: Final Report of the Defense Science Board Task Force on Wideband Radio Frequency (RF) Systems

I am pleased to forward the final report of the DSB Task Force on Wideband Radio Frequency Systems. The task force was asked to review and advise on key aspects of the policy and technology issues associated with the military applications of wideband radio frequency systems. To do this, the task force reviewed technical issues associated with wideband radio frequency modulation; technical issues associated with spectrum management; implications of employing wideband radio frequency modulation, network services issues, interference issues; and cost and technical risks.

The report addresses near-term and far-term wideband radio frequency research and development issues and spectrum management and policy issues for the Department of Defense. The task force supports actions by the Department of Defense to take the lead in offering new radio communications technologies and new strategies and policies to the larger national and international communities.

I endorse all of the task force's recommendations and propose you review the Task Force Chairman's letter and report.

William Schneider, Jr.

William Schneider, Jr.
Chairman

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OFFICE OF THE SECRETARY OF DEFENSE
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DEFENSE SCIENCE
BOARD

MEMORANDUM FOR THE CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Final Report of the Defense Science Board Task Force on Wideband Radio Frequency Systems

Transformation of the U.S. military requires communications systems that are agile, adaptable, high-capacity, network-centric, efficient, and robust. Understanding how to concurrently achieve these goals is no easy task. Even though radio communications systems are in a state of worldwide flux, there are also many promising developments in the field of communications technologies.

The task force was asked to examine wideband radio frequency systems and evaluate them based on a range of criteria outlined in the Terms of Reference. The task force performed a broad review of current research projects, both commercial and government, and considered them in the context of current Department of Defense (DoD) capabilities and ongoing research and development efforts.

In order for the DoD to push forward the vision of transformed military communications systems, the task force has considered both technology and policy improvements to address the future of these systems and recommends:

- A comprehensive program in agile wideband communications systems;
- Increased and focused investment in flexible and adaptive agile wideband communications technologies;
- Establishment of a testbed appropriate to these systems;
- Identification of an office for network centric communications and the development of a roadmap for these technologies and architectures; and
- Leadership of DoD in demonstrating both stewardship of allocated spectrum and advantages of wideband radio frequency communications.

This report argues that the DoD must embrace a technology development path that incorporates wideband technologies and institutes an organization that monitors and guides future radio frequency communications systems to achieve crucial mission requirements within an achievable budget.

Gary J. Minden

Dr. Gary Minden
Chairman

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EXECUTIVE SUMMARY

Radio communications is in worldwide flux. There are pressures from the commercial sector for additional frequency spectrum to provide new services; there is significant demand from the Department of Defense (DoD) to increase communications capacity around the world and in multiple contexts/environments; and there are multiple proposals for innovative radio architectures that promise greatly enhanced radio frequency capacity. This report discusses these aspects and presents a set of recommendations aimed at moving in a comprehensive manner to a coherent communications system for the Department of Defense.

Wideband radio frequency (RF) technology addressed many of these issues facing the Department of Defense regarding network-centric warfare. The technology offers high capacity communications links necessary to tie widespread sensors, to officers, and to weapons on target; it offers flexibility to meet mission goals, whether covert communications or networked task forces; it offers the means to interconnect terrestrial, airborne, space, and wired infrastructure into a comprehensive warfare network; and it offers the means to adapt to domestic and international spectrum management policies and recommendations.

Radio frequency spectrum management involves the interplay of technology, the physical world, economics and business, legislation and regulation, homeland security and national defense, national policy and international relationships. Recently, a number of themes have converged to cause significant reconsideration of how radio frequency spectrum is managed in the United States and on an international scale around the world. The important technology themes are:

- Advances in radio frequency circuits, analog/digital conversion, digital signal processing, field programmable gate arrays, and computer aided design tools enable one to build flexible radios with significant software control and processing.
- End-user interest in mobile access to information resources and strong interest from the commercial sector to develop and deploy new services raises the demand for spectrum.

- Requirements of national defense and homeland security place high demand on spectrum resources.
- Recognition that spectrum is woefully under-utilized due to dated regulations and allocation/assignment processes and that treating spectrum as a scarce resource leads to exorbitant license costs.
- Proposals to dramatically re-architect the modes and mechanisms for using radio frequency spectrum for communications of multiple types promise higher utilization and enhanced services.

The Department of Defense (DoD) demands robust, high capacity, and agile communications links in an extremely wide range of environments. Meeting such demands requires addressing technical research and development issues, integrating multiple systems (e.g. space, airborne, and ground based), and cooperatively addressing national and international policy and regulation issues.

The task force was asked to investigate six items in its Terms of Reference, summarized here:

- Identify technical issues associated with wideband systems and impact on DoD and other agency systems,
- Monitor interagency review of spectrum management,
- Examine implications of DoD use of wideband on U.S. positions at WRC,
- Evaluate impact of wideband on future mobile networks and other users,
- Evaluate flexibility of wideband RF systems to meet present and long ranged communications needs, and
- Identify and assess cost and technical risk of extensive employment of wideband systems.

The task force found there are many promising communications technologies, many if not most having been developed with DoD support, to achieve specific DoD communications needs. Research in wideband RF systems, advanced signal processing, and networking is especially active. Wideband RF systems promise significant capabilities for adapting to a wide variety of problems, including high capacity links, robust communications, sharing the frequencies with existing systems, agility in worldwide operation, and improving spectrum utilization. However, evaluation of individual technologies many times becomes bogged

down in arguing specific technical issues within a wide breadth of possibilities. The task force used two models to understand these technical tradeoffs. The first model, a RF Resource Space, helped us understand the tradeoffs between frequency, spatial extent, time, and signal format. The second model, a generalized communication channel, made explicit options in configuring a radio channel, for example, the tradeoff between compressing an information source and increasing transmission capacity. The task force found missing any architecture for network-centric systems. The lack of a network-centric architecture leads to technical bickering and limited progress towards a functional, integrated system. The challenges in formulating a network-centric system architecture and implementation roadmap are significant, but necessary to incorporate these many communications technologies into a capable network-centric warfighting system.

Spectrum management continues to be a topic of significant debate within the federal government. Following the DSB report on *DoD Frequency Spectrum Issues* [DSB2000] and many discussions in the commercial and academic sectors, a number recent activities are dealing with spectrum management. The FCC's Spectrum Policy Task Force was chartered to evaluate changes in the spectrum policy that will increase the public benefits derived from the use of radio spectrum. The General Accounting Office (GAO) has issued a number of reports within the last year indicating congressional interest. Private and public groups have open debates on spectrum policy issues. DoD has demonstrated the importance of spectrum in meeting its mission by reorganizing its offices; creating a Office of Deputy Assistant Secretary of Defense for Spectrum, Space, and C3; and engaging in discussions with industry and preparatory meetings for the World Radio Conference. DoD will continue to feel pressure for its spectrum resources from domestic and international sources and from the need to meet future worldwide missions, including homeland defense. Early engagement with the various stakeholders and demonstrated capabilities to increase spectrum utilization would benefit DoD.

Spectrum management, for DoD, continues to be a problem that must be considered in a worldwide context. First, spectrum management is a sovereign right of nations and subject to treaty negotiations. Given the multi-faceted nature of any specific mission, access to other nations' radio spectrum resources is as crucial as access to over-flight permission, port rights, and force basing rights. Second, commercial interests, domestic, international, and global, will use various national and international forums to advance their interests. These forums might be individual sovereign nations, regional consortia, international

treaties, or standards bodies. An emerging, and effective, way for commercial entities to influence spectrum issues is through sets of countries that do not have the significant spectrum needs of the United States. DoD must recognize these significant influences on spectrum policy; anticipate future trends in worldwide commercial services; fully participate at the earliest time and at the highest levels in these multiple international forums - and be fully prepared to rapidly adapt to shifts in international spectrum treaties, rules, and regulations.

To achieve the flexibility necessary for DoD to meet its worldwide missions, increase capacity, and increase spectrum utilization, radios will have to use the latest technology, be adaptive, and be automatically coordinated across the communications network. It will no longer be possible to optimize a radio communications link for a specific mission. Missions will come and go over time and the units involved in a specific mission will be assigned ad hoc. Thus, the radio communications network will be formed as needed. This implies that all components of the radios system must be "tunable" and managed by an external network manager. The challenge before DoD is the integration of multiple radio technologies <u>and</u> the network protocols, routing, and management technologies <u>and</u> the information dissemination technologies into an adaptive, mission oriented communications system serving the warfighter. This is a significant challenge that must be addressed in the near future.

As DoD communications requirements expand, the task force finds the cost of our systems can benefit from the advances in the commercial communications sector. Yet the demands of the DoD can be very specialized (e.g. non-commercial radio frequencies and wider operating ranges), resulting in small parts quantities and performance requirements beyond those of the commercial sector. In many cases, this obviates the opportunity to use commercial capabilities and components. Wherever possible new communications strategies should be designed such that they can capitalize on the technology investment and production base of the commercial sector but, where this does not yield results, investments will be required to minimize risk, reduce cost, and provide the required capability to meet mission objectives.

In general, the task force finds that the Department of Defense is best served by investing in and advocating wideband RF communications systems for future communications systems though coordinated research, development, and procurement; extensive experimentation, integration, test, and evaluation; and developing new policies and engaging the commercial sector through various bodies with solid experience.

In particular, to move this vision forward within OSD and the military departments, the task force recommends that:

1. The Office of Secretary of Defense must initiate a comprehensive program in agile wideband communications systems.

2. Assistant Secretary of Defense for Network Information and Integration (ASDNII) and Undersecretary of Defense for Acquisition, Technology, & Logistics (USDATL) should increase and focus investment in flexible and adaptive Agile Wideband communications technologies to achieve necessary mission capabilities in a highly dynamic RF communications environment.

3. ASDNII must establish an Agile Wideband Communications Systems Testbed.

4. ASDNII should identify an office for network centric communications and develop a roadmap for technology investment, evaluation, and transition into operational systems. The roadmap should indicate phase-in and phase-out of technologies and architectures.

5. ASDNII must take the lead in demonstrating stewardship of allocated spectrum and the advantages of agile wideband RF communications to develop and put forth spectrum policies based on experience.

The proposed wideband based systems are readily reprogrammable in the field and are inherently agile in space, frequency, time, and coding. The Joint Tactical Radio System (JTRS) is but a first step towards these agile wideband systems. Investment in wideband systems will positively impact necessary high capacity data links, critical missions, and adaptation to the varied and changing spectrum policy and regulation environment on a global scale.

The wideband communications/network management approach advocated in this report would be an extension of the widely discussed for Code Division Multiple Access (CDMA) approach. CDMA appears to offer a single control mechanism in which one can vary spreading, power, number of users, etc. It can be combined with other techniques, for example, data compression, frequency hopping, and steerable antennas, to achieve additional performance. However, sole selection of CDMA hinders other possible emerging technologies, such as

multiple-input/multiple-output (MIMO) or Space-Time Processing (STEP) advanced signal processing techniques. The approach advocated in this report is to consider CDMA an important component of a larger wideband RF approach that intentionally incorporates and evaluates new technologies on a continuous basis. Agility in spectrum, space, time, and signal coding "future-proofs" military radio investments against the rapid developments in waveform technology, some of which may render CDMA obsolescent in the desired deployment lifetime of military radios currently on the drawing boards.

Agility implies control. The investigations of the task force led it to recognize the emerging convergence of radio communications systems, networks, and the necessary future coordination between the two seemingly different technologies. Agile radios require new, network based, control mechanisms that must take into account spectrum resources, international constraints, physical limitations, timely mission needs, and rapid adaptation during mission execution. Technologies to implement the control mechanisms; steerable and compact antennas; high-efficiency power amplifiers and low-noise receiver; and advanced signal processing hardware are a few of the important investments. The convergence between radio communications systems and networked systems must be recognized and pursued through research and experimentation. Network control and routing protocols must be developed to support future agile radio infrastructure. Ad hoc network routing protocols must evolve beyond current "fewest hops/lowest cost" objectives to encompass a richer trade-off space. The future infrastructure will range from squad size, covert communications across several kilometers, to fiber-satellite-unmanned aerial vehicle-ground dissemination of timely information. The procedures of utilizing this advanced radio communications infrastructure must be investigated-developed-tried-deployed. The task force found little experience with new modes of dissemination. Innovative information dissemination procedures must be coordinated with emerging command doctrine.

Many systems must come together and operate together in challenging and extremely varied environments. The best assurance that multiple systems will interoperate is extensive experience. The task force recommends an Agile Wireless testbed be established within DoD to experiment with new systems, integrate and test emerging systems, and evaluate the performance and provide feedback to researchers and system designers for continuous improvement. The number of wideband communications/network managed systems is numerous, only experimentation and experience will provide guidance to implement and deploy the best possible systems.

Finally, the Department of Defense must recognize the many interests and forces on spectrum within the United States and around the world. DoD can take a leadership role in emerging policies by practicing "spectrum stewardship" and demonstrating, through the testbed, new systems and capabilities. DoD's position is strengthened by developing policy based on solid experience.

The body of this report first introduces the topic and reviews the Terms of Reference for this investigation. It then presents an introduction to technical communications for senior executives to the complex tradeoffs addressed. Next, it develops the findings in a detailed and systematic manner. Finally, it draws recommendations and conclusions summarized above. This report argues that the Department of Defense must embrace a technology development and architecture and develop a deployment path that incorporates wideband technologies and institutes an organization that monitors and guides future RF communications systems to achieve crucial mission requirements within an achievable budget.

CHAPTER 1. INTRODUCTION

The task force was asked to consider the implications of applying wideband communications technology to future Department of Defense (DoD) applications. To this end, the task force examined the current state-of-the-art in communications technology, reviewed government and industrial research, considered how the technology might influence future DoD applications, and what actions the DoD should invoke to take advantage of the available and future technologies. Wideband radio frequency modulation systems are of great interest to the Office of the Assistant Secretary of Defense for Network Information and Integration (ASDNII) because they offer the military potentially greater efficiency in the use of radio frequency spectrum, increased flexibility in establishing communications networks, and at the same time can offer protection against interference as well as low probability of detection.

Communications is key to the vision of network centric warfare. In Joint Vision 2020 [JCS2000], the Joint Chiefs of Staff put forward a vision of interconnected sensors, shooters, command, control, and intelligence based on pervasive communications. This communications-based interconnectivity would then provide operational information superiority, more complete battlefield awareness, and dynamic joint operations. Communications also plays a critical role in transformational efforts as outlined in the 2001 Quadrennial Defense Review (QDR) [QDR2001]. The QDR requires "leveraging information technology and innovative concepts to develop an interoperable, joint C4ISR architecture and capability that includes a tailorable joint operational picture."

However, the task force has concluded that the vision stated by both the Office of the Secretary of Defense and the Joint Chiefs of Staff will be difficult, if not impossible, to achieve given the current approaches and programs within the DoD. In particular, current programs continue to be focused on specific projects and do not consider wider system implications. While DoD talks about a "systems of systems," there is little value placed on putting programs in a larger context, on science of this "systems of systems," and on experiments with large communications systems. This report recommends directions DoD should take to bring vision to reality in network-centric warfare.

TERMS OF REFERENCE

The general direction of this study is summarized in the following statement from the Terms of Reference (TOR):

> *"...review and advise on key aspects of the policy and technology issues associated with the military applications of wideband Radio Frequency systems."*

The task force took the following issues under advisement in directing considerations:

- Identify technical issues associated with wideband systems and impact on DoD and other agency systems,
- Monitor interagency review of spectrum management,
- Examine implications of DoD use of wideband on U.S. positions at WRC,
- Evaluate impact of wideband on future mobile networks and other users,
- Evaluate flexibility of wideband RF systems to meet present and long-ranged communications needs, and
- Identify and assess cost and technical risk of extensive employment of wideband systems.

The draft TOR referred to "Wideband CDMA" systems. The task force asked to expand the terms to "Wideband RF Modulation," to include in the study an examination of emerging ultra-wideband systems. Ultra-wideband systems are emerging from the laboratory into products and deployment and claim significant capabilities related to wideband communications systems. The complete Terms of Reference is discussed in Chapter 4 and presented in Appendix A.

The term 'wideband RF modulation' can have several meanings. In this report, the following were considered:

(1) Use of a wide frequency range, generally contiguous, to achieve high data transmission capacity (large bits per second capacity). Sensors and aggregate links (e.g. Tactical Operation Center to

Tactical Operations Center or theater to CONUS links) are typical examples.

(2) Use of a wide frequency range, perhaps non-contiguous, to achieve covert or anti-jam capabilities.

(3) Use of wide frequency range, perhaps non-contiguous, to achieve agility and flexibility in spectrum utilization.

Second, the term 'code division/multiple access' (CDMA) can have several meanings. In this report, the task force considered the following:

(1) Spreading a relatively narrow band signal over a wide bandwidth to achieve robust and perhaps covert communications. Also known as "direct sequence spread spectrum (DSSS)."

(2) Using multiple orthogonal codes to allow several users access to the same frequencies at different times, such as CDMA.

(3) A structure for a cellular radio system as used in some commercial cellular services (e.g. IS-95 or W-CDMA standards).

In discussing various systems and options, the task force intends to ensure the meaning of terminology is clear.

While the TOR focuses on the technical aspects (e.g. sharing, flexibility, interference, risks) of wideband systems and the spectrum issues, the task force carefully considered the fourth item, the use of wideband RF modulation in the context of future mobile networks. A communications mechanism, for example wideband CDMA, or other and is used between traditional radios, networks, and services, promises a new synergy with significant capabilities.

The members of the task force were selected for their experience in a wide range of backgrounds. Members were included with backgrounds in (a) developing and analyzing new communications techniques, (b) designing and building commercial wireless communications systems, (c) building communications of many types for the government, (d) space communications, (e) software radios, (f) international spectrum management and policy, (g) sensors, and (h) mobile networks. The extensive experience of the task force members contributed to the comprehensive consideration of the issues and the recommendations of this report. A list of task force members is provided in Appendix B.

The task force addressed three major themes during its study: the current state-of-the-art in wideband communications systems; current domestic and international spectrum management and policies; and the integration of radio systems with networked information systems.

The task force ascertained the current state-of-the-art in wideband systems from presentations from the academic, commercial, and government sectors. The base questions that the task force considered are:

- What are the capabilities of wideband RF systems? Bandwidth? Error performance? Covertness? Sharing?
- What is the rationale behind such systems?
- Why is one able to consider such systems now? What is the enabling technology?
- Why might wideband systems perform better than conventional narrowband RF systems?
- What impact do these systems have on "in-place" or "existing" systems? What is the effect of raising the noise floor?

The presentations heard covered developed and deployed systems, laboratory prototypes, and research programs and projects. In its estimation, the task force adequately covered the current state-of-the-art in wideband communications.

The second item was to understand the current situation in spectrum management policy. This involved presentations from several DoD offices, the FCC, the Department of State, and industry. The current world situation with respect to terrorism and homeland security provided a context to raise questions and understand the issues of this complex policy/technology/capabilities conundrum.

The third line of examination was the interplay between communications (links) and mobile information networks. This relationship is crucial to realizing the network centric vision of the Joint Chiefs of Staff. The most advanced information systems are not useful if not inter-linked to many other systems and capabilities. While the task force considers this an important component of wideband communications, few expert counselors were available to discuss the issues associated with integration. The task force relied on its own judgment in this area.

The remaining body of the report is organized into five chapters. Chapter 2 presents two communication models suitable for framing the technology questions. Chapter 3 reviews current capabilities and emerging technologies relevant to wideband communications. Chapter 4 addresses each of the terms of reference, relates each to the material presented in Chapters 2 and 3, and presents the findings of the task force. Chapter 5 is a set of recommendations DoD should act upon with respect to wideband RF systems. Chapter 6 presents the conclusions of the study.

CHAPTER 2. REVIEW OF RF COMMUNICATIONS, CHANNELS, AND MULTIPLE ACCESS SYSTEMS

The task force invested a considerable amount of time understanding and developing a model for how to think about emerging communications systems. The task force believes the model presented below aids in framing and understanding the many complex issues in network-centric communications systems.

This chapter describes two models, one covering RF resources and the second the communications process, that aid in understanding the tradeoffs between alternate systems and establish the context for further discussion. Each of the TOR items is then addressed within the established context. The chapter concludes with a summary of the findings.

Advanced communication systems involve the coordinated use of space, time, frequency, and signal format (coding) - features of the electromagnetic spectrum. These emerging systems offer better utilization of spectrum resources and incorporate wideband RF. Achieving the radio communications capacities necessary for network-centric warfare will require such better use of the spectrum. Currently, technical trades in communications design are made to optimize individual features such as link efficiency, bit error rate (BER), and range. As the interplay among trade spaces for networking and communication channels grows, total system efficiency and performance will likely be achieved by sub-optimizing individual features. Future advanced communications systems will require the integration of high performance hardware, sophisticated signal processing algorithms and network enabled coordination to achieve their goals.

In this section, the task force reviews the work showing that RF communications/networking integration is a necessary endeavor to pursue. To a certain extent, some of the material may appear to be tutorial in nature. The task force believes a clear exposition of the basics will aid the understanding of the problem and the evaluation of alternatives. In this section, the capacity of an RF channel, the resources necessary to operate that link, the composition of sub-systems needed to make a communications link, how design trade-offs are made

to achieve desired communications properties, and sharing among multiple users will be addressed.

RF Propagation

Radio signals are subject to attenuation as they travel through space. The free space loss (FSL) equation predicts this loss. The natural free space loss can be used to limit the extent of radio transmission (e.g. higher frequency, higher loss, shorter distance, lower probability of intercept) or constrain the frequencies used for communications (e.g. longer distance, lower frequency). The FSL equation is:

$$FSL = 32.4 + (20 \log d) + (20 \log f)$$

In this equation, **d** equals the path length in kilometers and f equals the operating frequency in MHz. From the FSL equation, it can be seen that as distance or frequency is increased, so is the path loss. As the operating frequency of a communications signal increases, the ability to communicate to a receiver at a given distance decreases if other changes are not made in the communications system such as increasing antenna gain or transmit power. As frequency increases above 8 GHz, rain attenuation and eventually oxygen absorption add to the signal attenuation. The factor of 20 in the "20 log d" is the loss considering a distance measured from a typical vertical antenna. For dismounted units in a prone position, or for ground sensor mounted antennas, this path loss factor increases to 40 log d. Also, for non-line of sight (NLOS) paths (e.g. foliage) the attenuation problem becomes even more severe as the channel frequency increases. There are tradeoffs in the availability and location of spectrum that is usable for specific applications based on the laws of physics.

RF Channel Capacity Limits

A theorem, put forth by Claude Shannon in 1948, states that the capacity of a channel (in bits per second) is a function of the bandwidth, the signal strength, and the noise, given infinite time. The theorem states, for a single transmitter-to-receiver path:

$$C = B \bullet Log_2[1 + S/N]$$

C is the capacity in bits per second, ***B*** the channel bandwidth in Hertz, ***S*** the signal power, and ***N*** the noise power. This equation is extremely useful to

understand fundamental limits. Data transmission at any rate is possible for an arbitrary bandwidth provided an adequate **S/N** ratio can be achieved in the receiver. The actual data rate is less than *C*, and requires a sufficiently involved encoder/decoder be used to approach *C*. Therefore, if one wants to increase channel capacity while maintaining a given bandwidth, two things must be considered. Either more signal energy per bit must be transmitted or noise and interference per bit must be reduces. Depending on the communications link application, these adaptions could be significant. For instance, for a soldier mounted radio, factors such as power consumption, size, and weight must be considered when increasing transmission and/or processing power. On the other hand, if the communications link is between two fixed communications towers, these factors may not be an issue because the necessary infrastructure can be planned, installed, and supported. Therefore, one will see throughout this study report that channel bandwidth/RF spectrum availability has specific impacts on the operational characteristics for a specific application and vice versa.

Shannon's equation also embodies a number of assumptions. The equation assumes signals are infinite in time, it says nothing about the spatial extent of the signal (i.e. ability to reuse the same bandwidth in a different location), it assumes noise is characterized as statistically white and Gaussian noise, and does not consider the ability to eliminate known interference. While these are "system" issues, they must be taken into account in considering advanced communication systems, many of which exploit these assumptions in Shannon's Theory.

RF Resource "Space"

RF communications exists in a feature "space" of frequency, time, spatial extent, and coding.

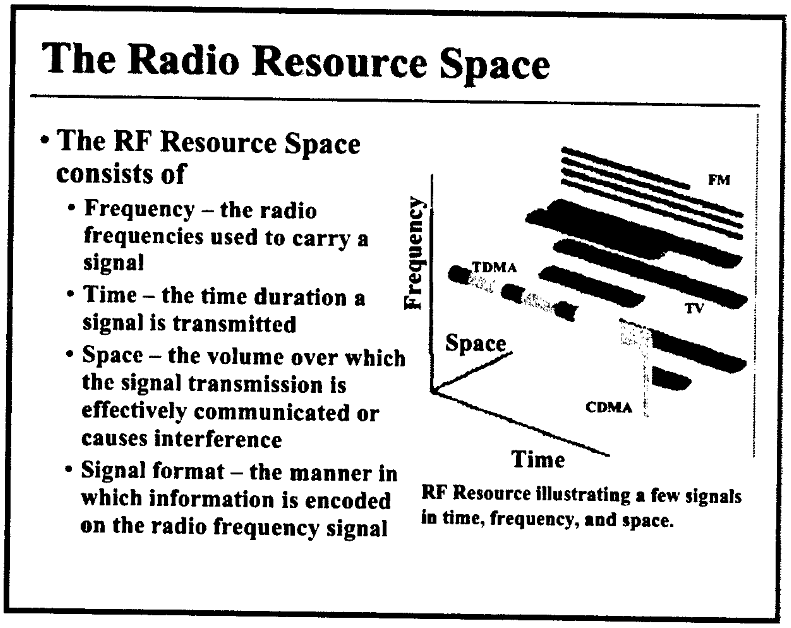

Figure 1.

Generally, interference between communication systems is avoided by separating different systems along these features of frequency, time, spatial extent, and coding. Frequency is the common method for separating RF signals. Each transmitter/receiver channel (Tx/Rx channel) is assigned a different frequency. Filtering at the receiver and transmitter eliminate interference from other Tx/Rx channels on different frequencies. Time is a second way to share the RF Resource. Tx/Rx channels agree on specific times to transmit/receive. Given sufficient coordination, several Tx/Rx channels can share the same frequency, spatial extent, and coding. One utilizes spatial extent when one implements directional antennas or takes advantage of multiple paths between the transmitter and receiver. Signal coding is the fourth primary means of multiplexing a Tx/Rx channel into the RF Resource. This form of multiplexing is feasible because each transmitter has available more of the resource than necessary to communicate its information, and pseudo-randomly selects the portion of the resource that it will use in any block of time. The most common means of coding is direct sequence spread spectrum (DSSS), however other techniques, such as ultra-wideband (UWB), are emerging. In DSSS, signals are spread by applying a pseudo-random code. If the receiver knows the code and is synchronized with it, the receiver can separate the desired signal from others that

use different codes and communication is possible. Several cellular telephone systems use DSSS, called Code Division Multiple Access (CDMA).

Coordination between numerous communications systems has generally taken place through a deliberative and well-engineered process. In the United States, this has been through the National Telecommunications and Information Administration (NTIA) and Federal Communication Commission (FCC) and internationally through the International Telecommunications Union (ITU). While reasonable at the time, these nearly manual processes have resulted in an under-utilized RF Resource and an extremely complex set of regulations. Understanding the RF Resource Space is a first step towards more efficient use of this resource.

Broadcast television and radio stations exemplify the sharing of the RF Resource. In the same region, television and radio stations use different frequencies to separate individual channels. However, the same frequency is reused separated by several hundred miles, relying on spatial extent to attenuate signals. Further, TV and radio stations change their transmit power levels based on the time of day, adjusting for different propagation characteristics during the nighttime.

Using the RF Resource Space, one can visualize the trade-offs between different communications systems. Each "feature" of the space represents a primary means of sharing the RF Resource: frequency division multiplexing, time division multiplexing, spatial multiplexing, and code division multiplexing. The RF Resource concept does not eliminate well established physical constraints, such as propagation loss or the Shannon limit. These, and other physical constraints, still hold, but the concept of an RF Resource Space enables one to characterize and evaluate trade-offs among several options. While this "space" of frequency, time, spatial extent, and coding is not a perfect Euclidian metric space, the task force believes it captures the essence of the resources available to the communications system designer.

Generalized Communications Process

The throughput of an RF communications channel depends on the bandwidth, signal power, noise power, and the spectrum resources allocated to the channel along with, and on other, information processing factors. Figure 2 illustrates the chain of communications processing.

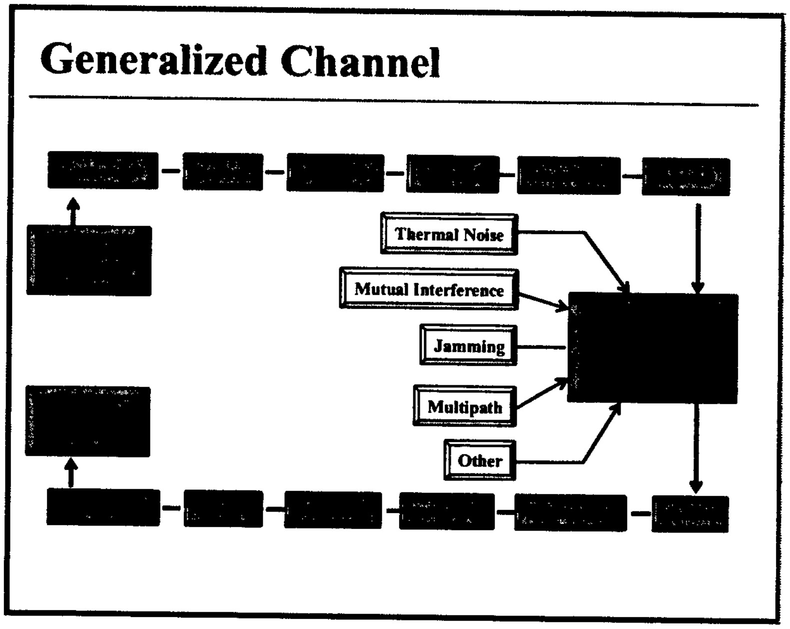

Figure 2.

Important factors in this processing chain are:

- Compression of the information (data). Data from the information source can be compressed using lossless (or perhaps loss techniques if appropriate) to reduce the number of bits that must be transmitted. Typical compression ratios can range from a few percent to thirty to fifty percent depending on the nature of the data and knowledge about the data.
- Error correction encoding. Additional bits can be added to the information to enable the correction of transmission errors. While adding additional bits to transmit, error correction encoding allows operation at lower signal to in-band interference (SIR) levels and may avoid retransmissions at higher protocol levels, a very 'time expensive' (high-latency) operation.
- Spreading. Information bits can be "expanded" where each information bit is replaced by two or more transmission bits by the exclusive-or with a spreading code or pseudo-random sequence. The

effect is to increase the bandwidth, and "spread" the transmitted energy across a wider frequency band. The signal to in-band interference ratio (SIR) can be converted to an equivalent signal to noise ratio (Eb/N) by good spread spectrum processing, with N representing the effects of both receiver noise and interference, and being higher than the density of thermal noise alone (No). Spreading may be done to increase the SIR or to multiplex several users on the same frequency band.

- Modulation. Information bits are used to change an RF signal.
- Transmitter power. The transmitter power is a key factor in determining the range of communications.
- Transmitter Antenna. The transmitter antenna effects the communications by its efficiency and, perhaps, focusing the emitted RF energy in a particular direction using the antenna structure or signal processing. Transmit antennas can "steer" a main beam toward the receiver and away from possible interceptors by "beamforming."
- Propagation (Power received). RF energy transmitted is affected by the environment. Some energy is directly 'carried' from the transmitter to the receiver, some is absorbed by the physical environment, some is reflected and delayed in arriving at the receiver, and some is modified in transit. Many things effect the transmission of the RF energy. The intended signal arriving at the receiver is a complex result of propagation.
- Interference. In addition to the desired signal, other RF energy enters the receiver. Inherent in all receivers is thermal noise, an artifact of the physical circuit. Other interference includes propagation effects, other users on the same system, other users on different systems, and jammers. All contribute energy to the receiver and make it more difficult to detect the intended signal.
- Receiver Antenna. The received signal is formed via a possibly multi-beam receive antenna. The receiver simply detects all RF energy in the receiver band.
- De-Modulate. The de-modulation step involves identifying the desired signal and, optionally, subtraction of noise/interferers. The resultant signal is compared against expected values and a decision is made to determine if the signal is a 1 or a 0 (Digital transmission is assumed). Different techniques of modulation and de-modulation

will lead to different performance and capabilities, including occupied RF bandwidth of the channel.

- De-Spreading. If the information was spread before transmission, the corresponding inverse de-spreading operation is applied to remove the effect, before or after de-modulation.
- Error Control. The transmitted data is checked for errors and if detected, correctable errors are to be corrected.
- De-Compression. The original information stream is recovered once the de-compression operator is applied.

The communications process is a complex system and has been "tuned" over time to achieve exceptional results in specific applications. The use of frequency modulation resulted in less noise in commercial radio broadcasts. The use of Quadrature Amplitude Modulation (QAM) has increased the number of TV channels broadcast over direct satellite services. It is important to recognize that all steps in the communications process must be considered in both the design and the deployment of a robust system.

Crucial DoD Communications Properties

Each step in the communications process described above is controlled by parameters and there are trade-offs between parameter settings for each step. For example, one might increase the effectiveness of error control by adding additional error control bits to the information stream. Increasing error control increases the communications overhead, reducing the user data rate. Another way to improve error performance is to increase transmitter power. Increasing transmitter power increases the probability of detection by an enemy.

Parameters of the stages of the communications process are set to elicit desirable system properties. Such system properties include:

- Jam resistance
- Low probability of detection
- Low probability of interception
- Foliage penetration
- Communications in adverse environments (robust communications)
- Communications distance

- Communications capacity

These properties are often mutually inconsistent. Improvements in one often result directly in degradations of others. Channel processing parameters also are constrained by system implementation and deployment criteria, such as cost, schedule, size, weight, ease of operational use, and power consumption. The value of each parameter setting can only be established in the context of the mission, cost of implementation, complexity of implementation, and other criteria. No single approach, or settings of parameters, will meet all missions.

Communications Channel Sharing

Finally, the task force addressed the issue of sharing the RF Resource Space among multiple users. The previous sections focused on models for one-to-one communications. However, in most situations it is important for many users to inter-communicate. To increase the utilization of the RF Resource Space, sharing mechanisms are employed. Traditional sharing mechanisms, as outlined above, are frequency division, time division, code division, spatial extent (beam-forming), and channel accessing schemes such as Carrier Sense Multiple Access (CSMA), where users contend for use of the same channel, and so forth.

When a portion of the RF Resource Space is underutilized, one implements mechanisms to share the common communications resource. This is possible when no single information source is sending data continuously, or one wants to exchange information between multiple senders and receivers. Generally, some aspect of the orthogonal, or independent, nature of the RF Resource Space is used to implement sharing, e.g. frequency, time, spatial extent, or coding. The effect is division of the finite communications resource among multiple users. If multiple users wish to communicate and each one does not require the complete RF Resource, then one can increase utilization of the resource, with proportional reductions in the capacity available to each pair of users by multiplexing the multiple users onto the same resource. The multiple users are sharing the limited RF Resource.

Spectrum sharing implies an allocation process, or mechanism, to assign a portion of the RF Resource Space to one or more information transmissions. The communications resources can be allocated on a permanent, or static, basis or intermittent (dynamic or demand access) basis. How this allocation is made determines some of the properties of a shared communications resource. A statically allocated resource is likely to show low utilization and low (access)

latency equivalent to a dedicated communications link. It also may fail catastrophically when a single critical link is damaged. A demand access system is likely to exhibit some delay in allocating the resource and even the possibility of blocking a transmission when no resource is available. However, a demand access allocation process will likely show higher utilization. Only a very few radio systems utilize dynamic allocation. The cellular telephone system dynamically allocates resources to users as they initiate a call or move from cell to cell. Some land-mobile systems use a "trunking" mechanism to allocate channels on demand.

The sharing/allocation mechanism includes an architecture describing how users are interconnected, such as who can communicate with whom, and how and where the communications resource is allocated. A common architecture is a hierarchy. The telephone system is designed as a hierarchy. Users connect to a central office. The central offices in region are interconnected through a toll office; toll offices may form a mesh network. Some toll offices connect to international offices for overseas calls. Given the long time line for implementation and known, historical traffic loads, the planned and hierarchical architecture suits the telephone system just fine. A different architecture is a completely connected mesh network. The common handi-talkie implements a mesh network in which each user can send information directly to any other user. Control of such mesh networks can be chaotic, as with Citizens' Band Radio. Hybrid analog and/or digital networks are also possible that are mesh networks at the lowest level, but each mesh network has a gateway to other mesh networks.

The architecture and allocation mechanism will determine such properties as the following:

- <u>Access latency to the network</u> - length of time from first request to time of first transmission
- <u>Blocking probability</u> - probability that a request for communications resources cannot be allocated
- <u>Transit delay</u> - length of time from sending first bit to receiving first bit (i.e. propagation delay across the network)
- <u>Latency jitter</u> - variation in transit delay among a set of transmissions
- <u>Robustness</u> - ability of the network to continue functioning in spite of damaged nodes or links, which may be mediated by routing and internetworking protocols like TCP and IP

- Setup time - time from first placement of nodes to operational status
- Adaptability - ability of the network to change organization and/or routine in response to changes in node location or the environment
- Join time - the time and ability for a new user to join an existing network and includes the necessary authentication and authorization checks
- Prioritization of access - gives high priority users first call on available resources

When many communication links are involved to cover a geographic area, packet networks provide certain economies in sharing the spectrum through the use of adaptive routing.

The high value of a common protocol to exchange information between networks has been demonstrated by the Internet Protocol (IP). The architecture of IP calls for a single protocol to exchange packets between networks. Many different transport mechanisms, such as transmission control protocol (TCP), user datagram protocol (UDP), and real-time protocol (RTP), can be implemented on top of IP. Further, many different applications can use the few transmission protocols and the single IP. IP can be carried on many different types of networks: wired, optical, radio, et cetera. IP packets are moved through a network from the source endpoint, through router to router, to the destination endpoint. At each router the header of the IP packet, containing the destination address, is examined and a decision is made on how to move the packet towards its destination. The decision process is implemented by an underlying routing mechanism and protocol.

Routers exchange information between themselves on which hosts or networks are reachable from each router using a routing protocol. The 'best' routes from a local router to remote networks are (usually) computed at each router. This approach works well for static or slowly changing network interconnects. However, it can take significant time for information on a change in connectivity to propagate across the network. This leads using outdated connectivity information and inconsistent routing decisions across parts of the network. Rapid dissemination of connectivity information, while improving routing decisions, could degrade user throughput on low capacity links. Further, routing protocols become a significant vulnerability if not suitably protected. An attacker breaking the routing protocol could cause significant havoc with just a few well placed packets.

Current protocols used in the Internet avoid, for good reason, knowing any characteristics about the underlying networks. This approach leads to ubiquitous connectivity. However, this approach also precludes taking advantage of or avoiding certain networks for certain applications. This is an issue in a network-centric architecture. Current routing protocols assume a relatively static network infrastructure and are overwhelmed with highly mobile network infrastructures. Even protocols that seemingly address mobility, Mobile IP and ad hoc networking for example, assume a relatively stable infrastructure.

Network protocols and network management for network-centric systems must also exhibit the following characteristics:

- Robustness – the network should strive to maintain connectivity, perhaps at the detriment of other properties. Routing algorithms may have to maintain multiple paths between source and destination and may have to anticipate future routes for high-speed nodes transiting the network. The network should degrade "softly" rather than abruptly.
- Security – access to the network should be protected, transmissions should be protected and authenticated, and "lost parts of the network" should be prevented from further participation.
- Set-up and recovery times – setting up the network should be automatic and require minimum time, i.e. order of seconds not minutes, and recovery from significant changes in the network, e.g. joining two major units, should also be accomplished on the order of seconds.
- Network Protection – the protocols and management systems must be able to deal with attacks on the network in an expeditious manner. Denial of service attacks, attacks against the signaling and control system, unintentional consequences (e.g. multi-casting high-bandwidth streams across low-bandwidth links), among many other events must be taken into account and dealt with.

The interaction between radio connectivity, highly mobile networks, and commodity protocols continues to be a challenging problem.

RF Communications, Channels, and Multiple Access

The previous sections reviewed the components, or sub-systems, of RF communications systems. Traditional design approaches work on individual components and seek to achieve mission critical communications properties through component design. However, as described above, there is extensive interaction between components and there are several approaches to achieving a particular communications property. The interactions, the multiple tradeoffs, and the requirements for wireless communications systems are complex. Few grasp the entirety of the communications parameter space. The result is a large set of projects focused on limited portions of the communications parameter space resulting in a lack of coordination and inter-operation between the individual systems. This is an extremely difficult task, but necessary given the network-centric requirements for RF communications.

CHAPTER 3. SUMMARY OF CURRENT CAPABILITIES AND ONGOING RESEARCH AND DEVELOPMENT

The following is a summary of current wideband capabilities and ongoing relevant research and development (R&D). The task force reviewed a number of research projects from government laboratories, government research funding agencies, the commercial sector, and the academic sector. The task force was impressed with the breadth and creativity of wideband communications systems and emerging capabilities. From our study it is clear that government, industry, and academia are interested and stimulated by the technical problems in wideband communications. The set of briefings indicate an excited and dynamic research community tackling the major problems in wideband communications.

GOVERNMENT FUNDED RESEARCH

At the basic research level, government offices are supporting all aspects of wideband communications. For instance, typical of the basic research efforts in very high-speed radio frequency circuits are:

- High Power, Highly Efficient, Linear, Wide Band-Gap Semiconductor Amplifiers
- 100 GHz Logic for Control and Direct Digital Synthesis to 25GHz
- 1.2 THz switching transistors
- 84 GHz logic
- Direct Digital Synthesis over 5 GHz
- 100 GHz, Ultra-Stable (goal of less than 30fs jitter) Clocks
- Very Wide Operating Band-Width Radiating Elements (Goal of five to one)
- Low Noise Amplifiers
- Tunable Bandwidth, Tunable Center Frequency Filters

The implications of this effort are that DoD, with continued investment, can anticipate increases in capabilities in the RF circuit domain, especially in the

future of ever higher operating frequencies where thus far uncontested bandwidth is available. RF circuits will be a significant enabler in future communications systems and capabilities. Assuming these research projects are successful, and there is reason to expect they will be, DoD should anticipate a continual shift from analog processing of communications (and radar) signals to digital processing. This shift will be extremely important at the higher frequencies, above about 10 GHz, but the capability to process signals at higher rates will also mean that more complex signal processing algorithms can be implemented for lower (carrier) frequency systems. Research in complex signal processing algorithms should be incorporated into future DoD plans for radio communications. The ability to use digital techniques, such as digital signal processing, high-speed microprocessors, and programmable gate arrays, will significantly impact DoD's communications capability. DoD should continue to invest in these research areas.

Government research laboratories are also investigating advanced communications techniques, such as orthogonal frequency division multiplexing (OFDM) and ultra-wideband (UWB). OFDM promises increased capacity within a multi-frequency system and UWB systems challenge conventional thinking of radio communications systems and regulations. Approaches that exploit joint time/frequency/space for modulation and coding, such as the work being performed at the Air Force Research Laboratory, show great promise for meeting the needs of those future systems requiring both agility and increased performance.

At Government Funded Development 6.2 and 6.3 levels, the task force also finds extremely interesting and worthwhile projects, but a lack of overall coordination of the research towards a network-centric system. Each project is justified as contributing to the goal of network-centric warfare, and is providing its contribution. But, it is not clear that many of these systems will inter-operate with one another and result in the type of system envisioned. There seems to be an implicit assumption that "the network," as represented by the Internet Protocols and ad hoc networking, will tie all of these communications systems together. That assumption avoids the complexity of ensuring compatible exchange between systems, multiple system management issues, and well-defined capabilities and properties.

The task force sees the Joint Tactical Radio System (JTRS) program as possible bridge between legacy waveforms and future wideband agile radio systems.

However, the task force saw limited evidence that JTRS is prepared to be this bridge. JTRS is a procurement program where the effort is to replicate existing waveforms to interoperate with existing systems without necessarily adding significant cross-system linking. This focus is constrained by the extended development/certification/procurement process and the need to work with existing systems. The JTRS program, while providing radio links, does not view itself in the larger network-centric vision, particularly in the area of network management. JTRS, a software based radio, could be the experimental platform to research and develop future advanced radio system concepts. The program should consider making radios available for experimental purposes to various research organizations.

The research and development projects performed by the DoD science and technology community are fundamental to future DoD systems and the task force does not want to diminish its importance. However, it is the integration, or even a plan for integration, the task force finds lacking. If an era of "systems of systems" indeed exists, then DoD needs to reflect that in the approach to research and development projects, especially at the 6.3 and 6.4 levels.

COMMERCIAL RESEARCH AND DEVELOPMENT

The commercial R&D that the task force reviewed fell into three areas: ultra-wideband systems, advanced signal processing techniques, and existing and code-division multiple access systems.

Ultra-Wideband Radio Systems

Ultra-wideband (UWB) radio systems are characterized by a large instantaneous fractional bandwidth with respect to the center frequency. Generally, if the quotient of the difference between the minimum and the maximum frequencies divided by the average of the minimum and maximum frequencies is greater than 0.20 - 0.25, the system is considered as ultra-wideband. (The upper and lower frequencies are commonly defined as the -10 dB points of the spectrum, relative to the peak.) The most common mechanism for generating ultra-wideband signals is to use extremely short current pulses, commonly called "impulses." The power emitted at each frequency can be somewhat adjusted by the shape of the pulse and the repetition rate. Other mechanisms can also be used to generate UWB signals.

UWB radio systems offer a number of advantages. First, the natural frequency diversity of the signal makes it possible for a receiver to do a better job of separating the signals coming over different propagation paths to the receiver. So for instance, if there were only two propagation paths, a narrowband signal coming over these paths would be added to itself, and depending on the phasing of the carriers, there would either be a strengthening or interfering of the signal, and it would look in time like a one-path signal. If the signal were UWB and the paths had a reasonable amount of differential delay relative to pulse width, these signals can be resolved and processed separately, and the amount of received energy is more spatially stable. Current hardware is quite limited in energy capture efficiency, i.e., the ability to use energy from many resolvable propagation paths, because it usually looks at the signal coming over only one or two paths. However, this is not a fundamental limitation, but one that may be overcome in future radio designs.

Second, the low power spectral density and wide frequency band provides covert communications and anti-jam properties, respectively, though these properties tend to conflict, or not be simultaneously achievable. The presence of low frequencies in the signal offers imaging and sensing through walls, and multiple users can share the same frequencies. The precise timing of received pulses can be used for precise location and identification, or tagging.

The imaging, location, and identification capabilities are perhaps the most important applications of UWB. For instance, UWB can be used in inventory management to locate and catalog equipment in densely packed warehouses or shipping containers.

Under current FCC regulations, UWB systems typically operate over a short range, typically less than 100 meters depending on data rate and propagation conditions, though some applications achieve relatively longer distances. This can be an advantage for covert communications or frequency sharing, or a disadvantage for larger scale communications systems. With suitable high power transmitters, the task force presumes communications over longer distances can be achieved, but this is yet to be authorized.

UWB radios challenge radio designers. Systems must operate and be power efficient over a wide range of frequencies and signal distortion in transmission lines and antennae reduces performance. Many UWB systems require a very precise clock at the receiver for a precise location function. This can be difficult to

implement. Detecting and locking onto an UWB transmission may also be difficult or time consuming.

The energy emitted by an UWB radio is distributed over a wide frequency range and, hence, there is a very low average power spectral density, or energy per Hertz. Some argue that the low power spectral density will not interfere with existing narrow band systems and that UWB radios should be allowed to co-exist with existing systems. However, many weak-signal systems, including those for radio astronomy, radars, receivers for covert transmitters, satellites, signal intelligence, and geo-location, such as the Global Positioning System (GPS) are designed to work with very small allowances for interference as they have small noise margins. Also, the impact of multiple UWB transmitters on the ambient noise floor must be considered since a specific S/N must be maintained for a given bit error rate (BER).

Because of the possibility for interference, the Federal Communication Commission (FCC) and the National Telecommunications and Information Administration (NTIA) in the United States, have been reluctant to permit operation of UWB radios. After significant debate, the FCC and NTIA allowed use of UWB radios in a limited frequency range and limited power. The emission limit for outdoor handheld devices is shown in Figure 3.

Note that the emission limit is at least -75 dBm/MHz between 0.96 GHz and 1.61 GHz to protect GPS receivers. If it were possible to perfectly fill this FCC spectral mask between 3.1 GHz and 10.6 GHz, the total equivalent isotropic radiated power (EIRP) would be less than 0.56 milli-watts. Hence, FCC compliance is a severe constraint that restricts applications to short range and/or low data rate communications. While the FCC will continue to review its UWB regulation from time to time, it is not expected that the UWB limits will change in the near term.

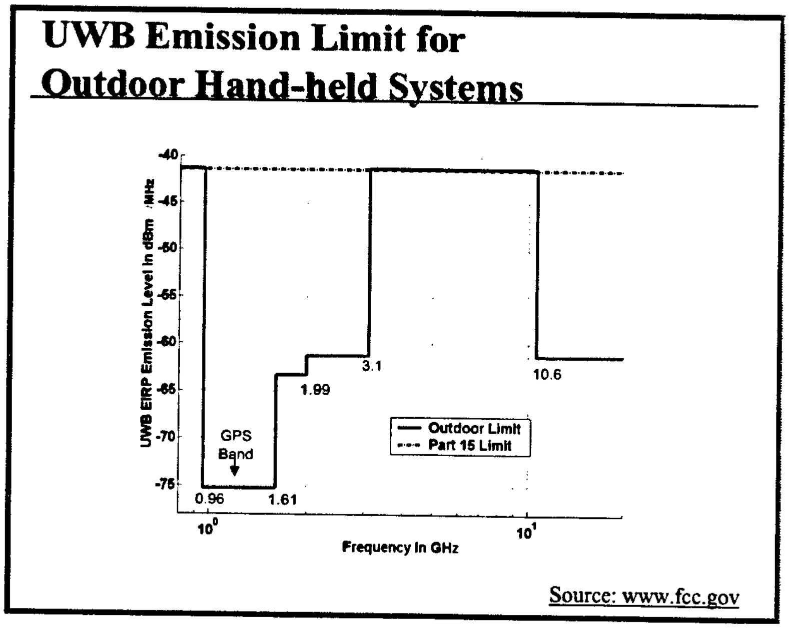

Figure 3.

The primary concern with UWB radio systems is that not enough is known on how these systems interact with existing systems. The regulatory community has acted on the side of caution. Limiting the knowledge of these systems is the lack of production radios as manufacturers are reluctant to commit to production without knowing the regulations; protection of intellectual property; unknown system properties (e.g., pulse repetition rate and protocol); and aggregate effects. Further, there is nothing in the FCC rules and order that prescribe modulation formats. As long as spectral masks are satisfied and a few other requirements are met, a system qualifies as UWB. Thus, any system that meets the power spectral density mask qualifies as an ultra-wideband system. Some studies such as NTIA, United Airlines, and the DARPA NetEx Program have preliminary results and almost all call for further study. Singapore is setting up an Ultra-wideband Friendly Zone (UFZ) in their research park, and in that area is considering a mask similar to the FCC mask, but higher by 6 dB in the 3.1-10.6 GHz band.

In the situation in which some narrowband interferers are present, spectrum management algorithms may be needed to manage UWB transmission and reception. That is, the transmitter and receiver have to cooperate in their transmission and reception techniques to avoid or mitigate the narrow band

interferers, such as friendly systems on transmit and receive, unfriendly systems on receive.

More research is required to understand UWB radio systems and their interactions with narrow-band radio systems.

Advanced Signal Processing

Industry is making significant investments in advanced digital signal processing techniques. One can see this in efforts to (a) develop and standardize software-defined radios, such as the Joint Tactical Radio System (JTRS), (b) use digital processing techniques much closer to the radio frequency front-end (the circuitry connected to the antenna), (c) build higher capacity systems, and (d) build more robust systems.

The ability to operate digital circuits at higher clock rates and the increased density of logic gates per square centimeter enables these systems. US government laboratories and sponsored research will drive digital processing and the conversion from analog to digital processing further in the next several years. The trend not only places radio signal processing on the so called "Moore's Law Curve," a doubling of circuit density every 18 months, but also opens up the opportunity to use more complex processing algorithms that are too expensive to implement in analog hardware.

One example of this trend is the multiple input/multiple output (MIMO) transmission scheme exemplified by Lucent Technologies' BLAST system. BLAST significantly increases the capacity of a point-to-point radio communications link by taking advantage of the multiple signal paths. Normally, radio engineers consider multiple signal paths a problem (e.g., multipath and fading degradation). However, BLAST purposely uses multiple signal paths to increase the capacity of the available channel. This is accomplished using multiple transmitters and receivers along with the necessary signal processing. BLAST requires significant, and continuous, 'sounding' of the channel and updating of the channel characteristics to achieve a significant capacity improvement over a single input/single output communications link. There are operational impacts which must also be addressed, such as the additional transmit/receive pairs for each antenna element, and the number of elements allowable on a given communications platform. Factors such as weight, size, power consumption and ease of operation must also be considered.

Space/time processing, in which one uses multiple antennas and transmits the same data at slightly different times, can improve the robustness of the communications channel. Most people have experienced the dropout of a radio, such at FM or cellular, channel while in a particular position. Slight movement in any direction removes the problem. This is signal fading usually due to multiple propagation paths canceling each other. STEP offers a range of techniques to reduce or eliminate these effects and maintain the communications link.

A second important signal processing technique is that of identifying interfering emitters and, by identifying those emitters, eliminating, or subtracting, their signal from the intended received signal. This is an extremely powerful technique. The technique can be used to increase the utilization of the RF Resource Space of multi-user systems and can be used to eliminate known emitters in the area. The technique implies knowledge of other users and interferers and those signal characteristics. Advanced theoretical work is developing new techniques and algorithms to determine the structure of signals without prior knowledge. These techniques could be used to adapt to the local environment. Operational impacts must also be considered, if there is a need for additional antennas and other RF components.

It is important to realize that the transition from analog to digital processing is not just a replacement of the analog algorithms with digital implementations. The incorporation of digital techniques at the most basic radio signal processing levels allows one to use significantly more complex algorithms which result in significantly increased communications system capabilities and properties. The task force will discuss the interaction of these advanced radio signal processing techniques with higher level network services later in a following section.

Second, these advanced signal processing techniques require significant processing, or computing, power and there is a corresponding size and power requirement to implement these techniques.

Code Division Multiple Access Systems

The task force surveyed many types of 'wideband' techniques and the associated spread spectrum and multiple access methods. The term *spread spectrum* refers to the process by which the bandwidth of the RF transmission is increased substantially beyond the minimum required to transmit the information in a particular modulation scheme. *Multiple access* describes the

manner in which multiple user signals are transmitted through a common channel in a substantially non-interfering way.

The two most commonly encountered methods of spread spectrum (SS) are direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS).

DSSS systems, sometimes called pseudonoise (PN) systems, employ a key generator to produce a high speed binary code sequence. An information signal is combined with this code sequence. This composite signal is then used to modulate an RF carrier. The code sequence determines the RF bandwidth, resulting in a spread spectrum signal. At the receiver another key generator produces a replica of the transmitter's code sequence, and the incoming RF signal is multiplied with this sequence. This collapses the RF bandwidth into a bandwidth which is commensurate with the information alone. Conventional narrowband demodulation techniques are then used to recover the information signal from the RF carrier. The critical problem in direct sequence systems—acquisition—is to synchronize the transmitter and receiver key generators [FCC1981].

In FHSS, the carrier frequency is periodically switched to a new value within a spectral region much larger than the baseband bandwidth of the data-bearing signal. A receiver 'dehops' the input signal to recover an IF or baseband version of the information.

A third method, time-hopping (THSS), deserves mention because of its relationship to another technique that was considered by the task force. In THSS information is modulated onto a pulse whose duration is very short compared to the inverse of the information data rate, and the location of the pulse changes pseudo-randomly within the allocated pulse slot from transmission to transmission. Because of the short pulse use, THSS resembles ultra-wideband (UWB) techniques. In its wideband review, however, the DSB chose to distinguish between spread spectrum and UWB systems on the basis of the typical service volumes associated with each in terrestrial applications—spread spectrum techniques, as used in cellular telephony or wireless LANs operate over tens of miles, whereas the range of UWB is usually on the order of tens of feet.

Hybrid SS systems can be constructed—as an example, a DSSS code can be frequency hopped over a wider bandwidth to create DSSS/FHSS.

In a communication channel dominated by receiver noise the various spreading methods offer little to choose among in terms of typical performance measures—e.g. error rates for the bit, word, or frame. Such comparisons should be drawn under circumstances of equal *processing gain*, conventionally defined as the ratio of the spread bandwidth to the information data rate. Where distinctions may arise among SS techniques, however, is in their antijam or detectability properties.

The allocation of AM/FM radio channels is an example of (non-spread spectrum) multiple access, in this case in the frequency domain; this may be called frequency-division multiple access (FDMA). Access by *time* slotting is TDMA; that by multiple, co-channel DSSS *codes* is CDMA. The ability to distinguish among signals on the basis of their strength at the output of a receive antenna gives rise to space-division, i.e. SDMA. Discrimination may be based on either physical (path loss) or angular (antenna pattern) separation. As for SS, hybrid access techniques are formed from combining two or more of the basic types, e.g. CDMA/TDMA.

Any form of multiple access may employ either a deterministically assigned or contention-based method of access. That is, access may be granted by an authority following a request, or open channels may be seized under control of a protocol that eventually resolves the contention and grants exclusive use to one user in the short term. A generic example of contention access is carrier-sense multiple access (CSMA), in which a receiver scans channels, looking for energy, and may attempt to access any channels found not in use. The distinction between the two methods is really based on whether contention is resolved before or after RF transmission in the communications channel commence.

The task force reviewed several CDMA systems, both commercial and military oriented, see Table 1. The systems examined primarily use DSSS modulation and CDMA techniques to achieve various system properties, e.g. multiple users, covert communications, low probability of intercept (LPI), low probability of detection (LPD), anti-jamming (AJ).

The task force believes that a joint appraisal of the status of both military and commercial communications systems is key to developing appropriate guidance for future government developments. More than ever, the technology bases of the two arenas overlap, and the capabilities offered by commercial systems become of great interest in an era where the government increasingly relies on

out-sourced services rather than proprietary systems. These issues are sufficiently important that three years ago the DSB itself addressed them in a report devoted to "an examination of private sector sources of technology, acquisition support and test and evaluation as well as processes for obtaining private sector support" [DSB2000-6].

Government Program	Commercial Program
GPS	Omnitracs
JTIDS	Globalstar
NTDR	IS-95
FCS-C	cdma2000
DSCS	W-CDMA
TDRSS	IEEE 802.11b
CDL	
JTRS	

Table 1. Representative government and commercial CDMA systems.

CDMA had been used in military systems since the 1970's and developed into a digital cellular telephone system standard, known as Interim Standard-95 (IS-95) by the 1990's. It may be noted that commercial utility of spread spectrum had been advocated to the FCC long before the advent of IS-95. In a 1981 report on the efficient modulation, the FCC observed, "The low power density and interference suppression capability of spread spectrum systems suggests a unique application,...band overlay. It may be possible in some circumstances to overlay spread spectrum systems on spectrum used by conventional services with little or no mutual interference....Short range systems, such as cordless telephones, might prove ideal for such an application" [FCC1981]. In this and related passages in the report, the FCC uses the term "spread spectrum" narrowly, essentially equivalent to the present use of "CDMA."

Justifications cited by FCC for this viewpoint remain valid today, some having assumed increased importance. Among them are selective addressing, uncoordinated sharing of a frequency channel, low power spectral density, ability to track a spread spectrum transmitter and interference rejection. Among all discussed properties, only one, which related to spectral efficiency, bears a

cautionary note concerning the potential impact of mutual interference and the near-far effect on spectral efficiency.

To the FCC's favorable citations, others may be added that are derived from DoD's projected needs for autonomous, net-centric communications in a service-on-demand environment. Among the reasons why CDMA merits consideration as an enabling technologies for future DoD networks are: (1) high data rate, AJ, LPI, LPD and mobile ad hoc networking (MANET) capabilities have been demonstrated in prior programs; (2) a large DSSS commercial base exists to leverage commercial investment; and (3) CDMA in its hybrid forms is well suited for the envisioned (advanced and dynamic) spectrum management options in the future. In defense of the latter claim the task force noted that the absence of world-wide, dedicated, primary-use spectrum to service all DoD needs drives the pursuit of a spectrum aggregation policy to implement the derived communication requirements, mandating that the supporting technologies exhibit features and flexibilities compatible with that approach.

The need for novel spectrum access methods for DoD is presupposed on the basis that it seems unlikely that answers to DoD's future spectrum needs are to be found within the currently accepted U.S. and international spectrum access regulations. Mounting evidence for this can be found domestically in recent reports of the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC), in which the SPTF examines current spectrum usage models and, upon considering documented evidence that there is considerable and somewhat unpredictable amount of peak-to-average usage fluctuation in a variety of assigned bands, including some of the most sought-after U.S. spectrum—the VHF/UHF public sector allocations—finds it reasonable to begin addressing alternative access paradigms exploiting previously unused allocation dimensions, such as time and in-band noise floor, or interference level, to improve the efficiency of spectrum use [FCC2002-11].

CDMA, as represented by the Qualcomm-developed IS-95B cellular telephony standard, constitutes high-visibility proof that CDMA systems will work up to their theoretically anticipated limits in the real world. IS-95B employs one form of CDMA—single carrier—among several varieties, and though not fully representative of the scope of offered capabilities, commercial CDMA does illustrate many of the best usage modes for CDMA in other contexts.

MeshNetworks, Inc. has developed an ITT Industries patent into a commercial CDMA hybrid called Quadrature-Division Multiple Access (QDMA). Using simultaneous transmission of a communications channel and a control channel, each spread by different PN codes, QDMA facilitates restricting communications on the network to a particular conversation mode and between identified radios. Transmissions are performed in a network-referenced time division duplex format having 16 slots per second. A user radio (the one initiating transmission) becomes a network controller that maintains power control and time synchronization, normally functions allocated to a base station. A network control station can voluntarily or by command transfer control of the network to any of the other radios on the network. Carrier-sense multiple access (CSMA) lets radios contend for open slots until one of the radios captures the slot.

QDMA partially addresses some major concerns for military CDMA, in particular the normal requirement for a base station of unique capability that consequently becomes a single-point failure liability. It accomplishes this by shedding throughput to avoid the hard timing issues of OCDMA, replacing orthogonality in code and frequency by that in time. This approach, undoubtedly not a turn-key solution for DoD, contains elements of interest and should be extrapolated to scenarios modeling future DoD requirements.

The task force finds the following aspects of CDMA favorable to the needs of future DoD networking:

- CDMA implements flexible channelization in which capacity saturation is approached gradually rather than abruptly as may occur in fixed-allocation TDMA or FDMA
- Multi-carrier CDMA and other hybrids incorporating filter bank technology offer the potential for non-contiguous band allocation and/or novel approaches to frequency diversity
- Efficient techniques for accommodating data rate variations versus time exist and are likely to be refined in the commercial sector
- When typical MANET issues such as flexibility, connectivity, availability, and equality of resources for all net members are of greater concern than operation near a throughput maximum, CDMA/TDMA hybrids offer operation without near-far interference or requirement for a fixed-function base station—an example is QDMA; hybrids deserve increased attention in connection with

programmable signal formats, since different (or differently parameterized) hybrids may serve some applications better than others

- Unlike frequency-hopped systems, CDMA is instantaneously wideband and thus has somewhat greater resilience to sophisticated jamming and detection threats
- Beyond their function in communications, CDMA signals can provide timing (or pseudo-range) measurements that may augment a host platform's navigation and guidance system(s)

Lingering questions about CDMA identified by the task force include:

- High throughput requirements are typically met via hub-spoke architecture, which places a significant burden on the hub—or base station— node, creates undesirable single-point vulnerabilities and forces a symmetrical frequency-division duplex spectrum allocation requirement
- Despite the great variety of architectural, signal format and protocol fixes to be had, non-orthogonal forms of CDMA are always subject to service degradations brought on by the familiar near-far problem
- Use of orthogonal CDMA (OCDMA) can eliminate near-far effects within a controlled subnet; synchronization of multiple transmissions for orthogonality is easy, but adjusting receive times when multiple sources transmit simultaneously may require additional time-frequency measurement and control overheads that rob capacity while increasing a terminal's processing load; OCDMA is promising but untested
- Although power control can mitigate much potential interference, either within subnet or to other uncoordinated subnets, further research is needed to determine the extent to which power control complicates MANET CDMA
- Legacy operating procedures inherited from the commercial CDMA world are less than fully appropriate to MANET situations—see Table 2; realization of CDMA's potential relies on synergistic development of related network technologies

Cellular Network	Ad Hoc Network
Fixed, pre-located cell sites and base stations	No fixed base stations, very rapid deployment
Static backbone network topology	Highly dynamic network topologies with multi-hop
Relatively benign environment and stable connectivity	Hostile environment (losses, noise) and sporadic connectivity
Detailed planning before base stations can be installed	Ad hoc network automatically forms and adapts to changes

Table 2. Differences between ad hoc and cellular networks.

These differences between commercial cellular networks and mobile ad hoc networks mean that it would be difficult to directly apply commercial CDMA cellular technology to DoD mobile ad hoc networks.

CHAPTER 4. TASK FORCE FINDINGS

TOR ITEM 1: TECHNICAL ISSUES ASSOCIATED WITH WIDEBAND RADIO FREQUENCY MODULATION

The TOR states: *The Task Force will identify the technical issues associated with the employment of Wideband RF modulation by the Department of Defense and defense-related agencies and its potential impact on other defense and non-defense users of the RF spectrum. In particular, the implications of DoD use of Wideband RF modulation as an alternative to a requirement for additional RF spectrum allocation(s) for the DoD should be assessed.*

Chapter 2 described models of communication channels to better understand complex radio communications systems and Chapter 3 reviewed the state-of-the-art of communication sub-system technologies, respectively. The important findings of this review are:

- Radio and networking technologies are available to implement and deploy wideband communications platforms.
- Future radios must be designed as an integrated system rather than independent components and designed to interoperate with a broad range of platforms. Communications technologies from antennas to network protocols, and everything in between, must work together as a seamless whole.
- Future radios will coordinate activity over a network to increase capability.
- Radio communications platforms should be adaptive and readily configured to DoD mission needs.
- Computer-based signal processing will significantly increase radio platform capabilities.
- Adaptability and increased capabilities are necessary to meet DoD wireless capacity needs and reduce demand for additional RF spectrum.

The task force conclusion from this review is that wideband RF systems are ready for advanced development and deployment.

Wideband RF technologies will be used to meet a number of DoD missions - high capacity links, reduces transmission errors, covert communications, spectrum sharing, and multiple access. However, meeting these missions simultaneously with a single approach is not feasible. For example, covert high capacity links are unlikely, as are many users networked together sharing, while not interfering with, another allocation. Wideband RF technologies, along with tunable radios and networked management, provide DoD with the mechanism and opportunity to meet its varied missions.

As reported in Chapter 3, the task force examined a number of commercial and military CDMA systems. Almost all of these systems were designed for a single purpose and defined infrastructure. One does not find in these systems the agility believed necessary in a network-centric mission. Many of these systems are point-to-point or point-to-hub architectures that rely on a media access control (e.g. IEEE 802.11b) or on orthogonal spreading code and strict power control (e.g. CDMA cellular). Media access control is a RF resource allocation mechanism for sharing the same spectrum among multiple users. CDMA cellular systems require strict power control to minimize interference between users. No one has worked out the details of how CDMA might actually work in a highly mobile, ad hoc network.

Chapter 3 also discusses the need to integrate network based management and flexible radio links. The task force found little work in this area. There is some work in the U.S. Army/DARPA Future Combat Systems Communications program on managing directional antennas, but in general, the ad hoc networking community is mostly concerned with simple routing issues and assumes unidirectional antennas and a simple receiver range. Directional antennas, frequency flexibility, modulation flexibility, coding, i.e. the components of the generalized communication channel, have not be considered. Bringing these factors into a mobile network management mechanism is a complex problem that must be addressed to realize the potential of wideband systems.

Electronic technologies are available to build wideband RF systems. The behavior of individual components is well understood. To achieve the dynamics necessary for network-centric warfare requires tunable radio components and network based management systems. Through focusing on these issues, DoD

should increase it utilization of RF spectrum and achieve it's vision of network-centric warfare.

TOR ITEM 2: REVIEW THE TECHNICAL ISSUES ASSOCIATED WITH SPECTRUM MANAGEMENT

The TOR states: *The review of the technical issues associated with the employment of Wideband RF modulation by defense related agencies should take account of the concurrent interagency review of spectrum requirements for advanced wireless mobile services led by the National Telecommunications and Information Administration and the Federal Communications Commission.*

The situation in spectrum management policy can best be characterized by "many actors, no director." The distributed nature of spectrum management in the U.S. Government makes it difficult for any one entity to take the lead in spectrum policy and management reform. The actors are the Department of Defense, the Federal Communications Commission, the National Telecommunications and Information Agency, other agencies, the commercial sector, and private think tanks and individuals.

Department of Defense Spectrum Management

The Defense Science Board raised the issue of spectrum management in a study published in November 2000 titled, "Coping with Change: Managing RF Spectrum to Meet DoD Needs." This report initiated some changes within the Department of Defense and raised the issue of spectrum management and policy as it relates to national defense and economic development. The report is the basis of a number of discussions on future spectrum management and policy.

Within the Department of Defense, the Defense Spectrum Office was organized under the Director of DISA and a new Office of Deputy Assistant Secretary of Defense (DASD) for Spectrum, Space, Sensors, and C3 Policy was created. These offices coordinate activities between the Office of the Assistant Secretary of Defense for Network Information and Integration (ASDNII) and the Joint Staff. The Defense Spectrum Office (DSO) consists of a National Team, and International Team, and an Emerging Technologies Team. These teams handle most of the day-to-day spectrum management decisions. The DSO works closely with the Joint Spectrum Center which directly supports operational spectrum

management, maintains an extensive international spectrum management database, and manages electromagnetic environmental effects (E3).

While these new offices are encouraging, it continues to be unclear which office speaks for the Department of Defense on spectrum management policy matters. These organizations need to:

- Define long-term spectrum requirements, policy, and usage;
- Define immediate-term spectrum requirements, policy, and usage;
- Ensure all existing and new programs have a consistent plan addressing current and future spectrum needs;
- Catalog all current and planned spectrum usage by DoD systems;
- Catalog all international spectrum usage;
- Ascertain future/immediate conflicts between DoD systems/ programs and global commercial directions, needs, and directions;
- Engage at a high level in international forums/standards for emerging wireless communications systems;
- Continue support to operational units in the field;
- Continue investigation into electromagnetic environmental effects (E3) and interference between existing systems and existing systems and emerging systems (e.g. ultra-wideband);
- Develop a plan for emergency and wartime spectrum usage.

Federal Communications Commission Spectrum Policy Management

The Federal Communications Commission (FCC) manages all spectrum for Commercial and State and Local Governments including Broadcast, Cellular Telephone, Industrial and Public Safety.

The FCC initiated a study on spectrum policy coordinated by the "Spectrum Policy Task Force." The task force submitted a report to the commission in November 2002. The report is still under consideration. The task force was challenged with the task of "improving the way that the electromagnetic radio spectrum is 'managed' in the United States." The FCC task force followed FCC procedures and solicited comments from interested parties and held open

forums. The Spectrum Policy Task Force (SPTF) reported the following major findings and recommendations (quoted):

- *Advances in technology create the potential for systems to use spectrum more intensively and to be much more tolerant of interference than in the past.*
- *In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access.*
- *To increase opportunities for technologically innovative and economically efficient spectrum use, spectrum policy must evolve towards more flexible and market-oriented regulatory models.*
- *Such models must be based on clear definitions of the rights and responsibilities of both licensed and unlicensed spectrum users, particularly with respect to interference and interference protection.*
- *No single regulatory model should be applied to all spectrum: the Commission should pursue a balanced spectrum policy that includes both the granting of exclusive spectrum usage rights through market-based mechanisms and creating open access to spectrum "commons," with command-and-control regulation used in limited circumstances.*
- *The Commission should seek to implement these policies in both newly allocated bands and in spectrum that is already occupied, but in the latter case, appropriate transitional mechanisms should be employed to avoid degradation of existing services and uses.*

In general, the FCC SPTF recommendations are reasonable. However, this task force is concerned with "pure" market approaches. In a "pure spectrum market," DoD would compete with commercial interests for access to spectrum. Our concerns are that without a clear definition of the market (e.g. who can enter, the cost of entry, and the rules of the market) it is difficult to commit to a market approach. In a "pure market" approach DoD would submit to funding sources to maintain and innovate in spectrum resources. A British study [Cave2002] recommended "spectrum trading" for commercial purposes, but recommended an approach of "government reserving spectrum" for public services, such as "defense, the emergency services, science and aeronautical radar." There should be a distinction between allocations and licensing. As spectrum is allocated internationally, it would be difficult for a country to depend on market allocations, which could be quite different from the ITU International or Regional allocations.

The FCC has initiated a national discussion of spectrum policy and management. The Department of Defense must track these efforts; anticipate its needs and potential conflicts; coordinate with emerging service efforts; and clearly state its reasoned positions to ensure cooperation and coordination with the efforts at the FCC.

National Telecommunications and Information Agency Spectrum Policy

The National Telecommunications and Information Agency (NTIA) is responsible for coordinating all Federal Spectrum, including DoD Spectrum, through the Interagency Radio Advisory Committee (IRAC). IRAC has twenty-two members including three from DoD, which is a small representation considering DoD's spectrum needs compared to most of the others member agencies. NTIA coordinates with the FCC on an informal basis to bring coherence to federal spectrum management. The task force found little effort from NTIA on addressing future spectrum needs and management.

Reports from the General Accounting Office

The General Accounting Office (GAO) has issued two reports on spectrum management affecting DoD spectrum. The first, "Defense Spectrum Management: More Analysis Needed to Support Spectrum Use Decisions for the 1755-1850 MHz Band" [GAO2001] reviewed a number of studies, including DoD and industry studies, related to interference and possible sharing of this band. The report concluded that the information available and models for predicting interference and the impact of sharing spectrum were insufficient to make sound decisions. Understanding the capabilities of the systems occupying this band, interference models, and possible sharing or re-allocation strategies continues to be studied by several government agencies and industry groups.

The second report [GAO2002], "Telecommunications: Better Coordination and Enhanced Accountability Needed to Improve Spectrum Management," provides an "overview of the development of the legal and regulatory framework for spectrum management at the federal level and assess key issues associated with spectrum management at federal agencies." The report points out that the "FCC and NTIA's efforts are not guided by a national spectrum strategy" and "the challenges the United States faces in preparing for World Radio-communication Conferences...have raised questions about the adequacy

of the United States' preparatory process." Further, spectrum management within federal agencies is hindered by staffing and resource shortages.

A third GAO report was released in January 2003 [GAO2003]. This report, "Comprehensive Review of U.S. Spectrum Management with Broad Stakeholder Involvement Is Needed," focuses on spectrum management issues. The report examines,

> *market-oriented approaches to spectrum management and other issues. Specifically, this report discusses (1) concerns about whether future spectrum needs can be met, given the current regulatory framework; (2) the advantages of market-based mechanisms and how they have been applied to help meet future spectrum needs; (3) whether there are difficulties with using market-based mechanisms; and (4) if it is found that fundamental spectrum reform is needed, whether the current regulatory environment is conducive to facilitating such reform.*

The report recognizes that a number of discussions and reviews of spectrum policy and management are underway. However, the report indicates, "it does not appear likely that timely reforms can be agreed to amid the diversity of views held by stakeholders." Further, no single agency holds the decision-making authority. The report recommends the formation of an independent commission "that would conduct a comprehensive examination of current U.S. spectrum management." The commission should involve all relevant stakeholders.

The GAO reports and their frequency indicate there is increased interest from Congress in the spectrum management and policy issue and the probability of actions in this area in the near term is likely. The DoD should be aware of this activity and anticipate and participate in all discussions related to spectrum management with Congress and the GAO.

Department of State

The Department of State maintains a small office for International Communications and Information Policy (CIP) and "has the authority and the ultimate responsibility for establishing foreign telecommunications policy" [Gross2002]. A primary responsibility of this office is the coordination of the U.S. position on international spectrum allocations and policy.

International spectrum management is carried out at the International Telecommunication Union's (ITU) World Radio-communication Conference (WRC). The ITU is a United Nations organization that establishes world telecommunications standards, radio frequency allocations, satellite positions, and telecommunications rules. The WRC operates under a one nation/one vote rule and results of the WRC are formalized by international treaty. To achieve the goal of a winning vote on its position, the United States must form coalitions that will support its position. Depending on the nature of the U.S. position or opposition to, the United States may find it necessary to have bilateral and multilateral meetings with many countries prior to and during the Conference. Many nations in a region vote as a block and do so to seek economic and/or political advantage. Not all nations share the same needs as the United States has for global operation of radio systems for national security purposes, therefore, finding support is sometimes difficult and time consuming.

CIP coordinates with NTIA, FCC, and other federal agencies to develop positions and proposals for the WRC. The next WRC was scheduled for June 2003 and preparations started shortly after the last WRC. The United States continues to be hampered by the fact that the head of delegation to the WRC is appointed only a few months before the meeting. Therefore, the head of delegation has little time to understand the ITU procedures, the issues, and history; organize the delegation; and meet the other delegation heads before the actual meeting.

The organization for the next WRC appears much improved over previous years. However, the process needs continued improvement with respect to long term planning, working with other nations and regional groups, commercial interests, and balancing U.S. security needs versus commercial endeavors.

Spectrum Policy, Management, and Organization Discussions

There continue to be many discussions and forums addressing spectrum policy, management, and organization. DoD appears to be an active participant in these discussions and forums. Because spectrum management is receiving much broader interest from the various stakeholders, it is beginning to attract the attention of Congress. Many recognize the importance of spectrum for economic development and DoD must understand these forces and clearly articulate its operational needs and requirements.

TOR ITEM 3: IMPLICATIONS OF EMPLOYING WIDEBAND RF MODULATION

The TOR states: *Implications of the employment of Wideband RF modulation for U.S. positions at the future WRCs should be identified and assessed.*

The radio communications systems for network-centric warfare must operate in, and be compatible with, a global framework of commerce, national sovereignty, and mission success. Figure 4 illustrates many of the operational situations U.S. warfighters will encounter.

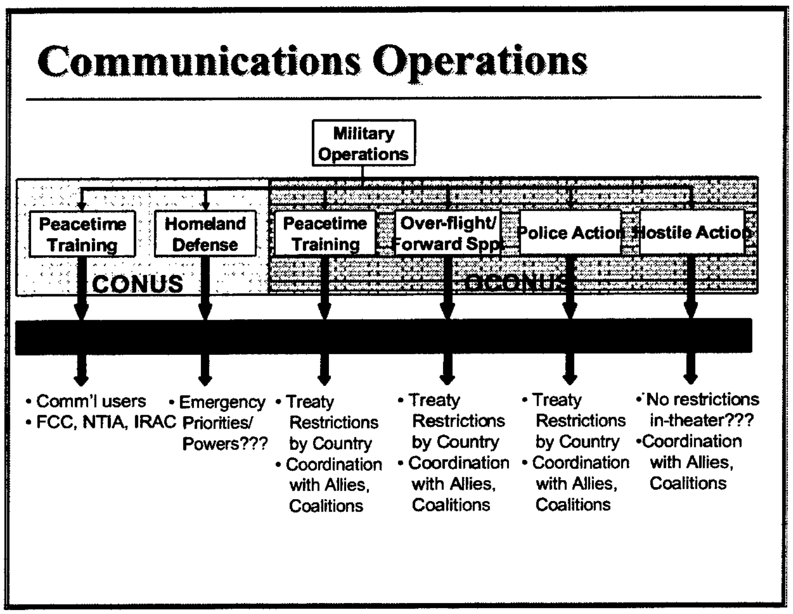

Figure 4.

Military operations span a wide range of activities. These operations take place inside the continental United States and outside the United States. Each type of operation and location places restrictions on the radio spectrum and communications capabilities that can be used and the way in which they can be used. Inside the United States, activities such as training and test and evaluation must conform to established domestic frequency allocations. In a homeland defense operation, communications with civilian authorities will be required and this will likely require interoperation with non-DoD, non-federal radio systems. Outside the United States, the military encounters spectrum usages constraints

depending on geographic location and activity. Almost all operations outside the United States will require interaction with coalition partners, whether a joint operation or access to facilities. Communications with coalition partners will have to conform to established allocations and rules in the locale. These constraints will hold even if the military is involved in a hostile action in theater. While there may be no restrictions or U.S. imposed restrictions in theater, military units most likely will encounter restrictions en route.

Another area where restrictions will apply is in training. Although a tactical communications system may have the capability to provide significant range and data rate in the United States, its capabilities may very well be restricted worldwide outside the U.S. borders, where effective radiated power (ERP), which is antenna gain plus transmit power, restriction will most likely exist. For example, restrictions occur while operating in the 2.4 GHz Industrial, Scientific, Medical (ISM) band where ERP for most of the world outside of the United States is limited to 10 - 100 milliwatts whereas a maximum of 4 watts is allowed in the United States.

Further, DoD must be aware that any significant disruption of other government or commercial services due (or even perceived due) to DoD operations will not be dealt with in the technical arena, but in the media, political, commercial, and diplomatic arenas. Incidents will be transformed from technical issues into political issues. And, even if the technical problems are resolved quickly, the political issues will have a long "half-life."

Regulatory Issues

The Defense Science Board Report on Spectrum Management [DSB2000] described in detail the interaction between the Federal Communications Commission, the National Telecommunications and Information Agency, the Department of State, and international bodies. The organizational chart is illustrated in Figures 5 and 6.

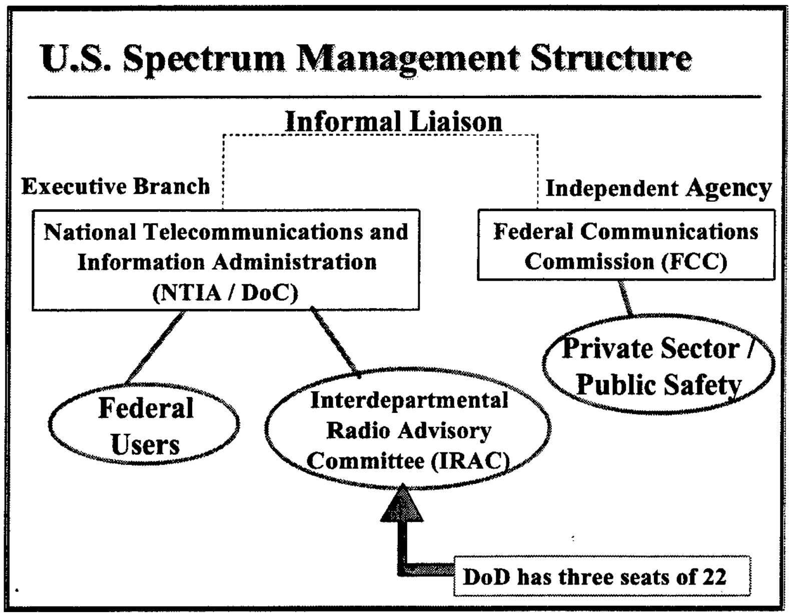

Figure 5.

Since publication of the DSB Spectrum Management report of December 2000, the issue of spectrum management policy has increased in visibility. Some of this attention is due to interest in fielding new wireless services by the private sector. Additional attention is brought by the immense cost incurred during recent spectrum auctions. Several organizations, including the FCC Spectrum Policy Task Force and the Center for Strategic and International Studies Commission on Spectrum Management are reviewing spectrum management policy and discussing possible new approaches. DoD is involved and should continue to be involved in these activities.

As described above, the Department of State is involved with international spectrum policy issues and maintains a small office following those issues. While this office follows the issues, the United States continues at a disadvantage in the international forum because its ambassador is appointed shortly (less than six months) before the ITU World Radio Conference. Subsequently, there is insufficient time to build the long-term relationships necessary in this forum and be aware of the issues and implications of proposed actions.

While at the time of the DSB Spectrum Management Study (1999-2000) the telecommunications industry was extremely active and "economic security" appeared to be reaching par with national security, the events of September 11, 2001 have shifted the focus back to national and homeland security. While this focus is fully justified, that does not eliminate pressure from the domestic private sector or the global private sector on spectrum resources and it adds to the requirements that DoD be capable of inter-operating with domestic public safety and law enforcement agencies.

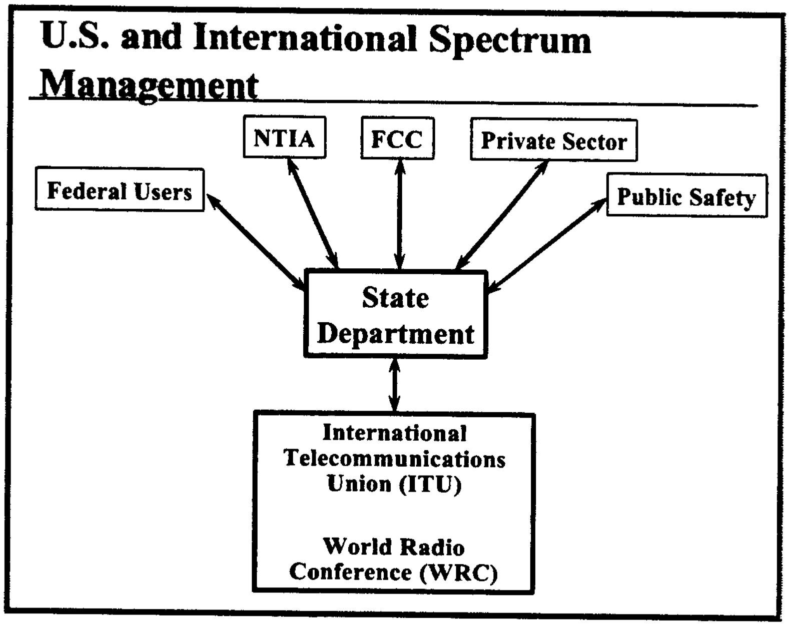

Figure 6.

The effects seeking additional spectrum resources the task force has seen and will continue to see include:

- Governments will support the growth of their industries in the wireless market by seeking global frequency allocations for new services,
- Domestic and international corporations will support global frequency allocations for new services to remain competitive through multiple "national bases",

- Corporations will use international standards bodies to embody global allocations and services,
- Corporations will use the U.S. organization and regulatory framework to embody global allocations and services, and
- Corporations will use lobbying efforts on regulators, federal departments, and Congress to achieve global allocations and services.

These are not necessarily new techniques, but a divergence of national policies may make the effects more intense. DoD must understand the sources of spectrum resource pressure and where and how that pressure is brought to bear. ASDNII recognizes many of these issues in their "Electromagnetic Spectrum Management Strategic Plan" [DOD2002]. Likewise, the regulatory bodies must understand the impact of frequency spectrum availability, and where in the frequency band it is available, on the operational capability of the warfighter.

Operations in the Regulatory Environment

DoD will continue to encounter conflicts in the regulatory arena. These conflicts will arise from the complexity of the DoD mission, recently increased by the new emphasis on homeland security. Domestic economic interests to provide new services and global businesses interested in seamless inter-operability will continue to challenge DoD spectrum resources. DoD must be an articulate voice for its worldwide needs in these various forums and be prepared, through advanced radio technology, to adapt to adverse decisions and environments to the maximum extent possible

TOR ITEM 4: NETWORK SERVICES

The TOR states: *The technical impact of the DoD employment of Wideband RF modulation on future mobile wireless networking and other users of the RF spectrum should be identified and assessed.*

Integration of wideband RF communications systems with information and networking services is crucial to network-centric warfare. This integration will result in new capabilities, including direct sensor-to-shooter communications, adaptive radio communications systems, and rich information services. Wideband RF systems are crucial to achieving these capabilities because they provide the agility necessary for many future missions. Wideband RF systems

can provide high data capacity, robust communications, and non-contiguous spectrum utilization, but perhaps not at the same time.

There are three forces pushing wideband RF communications systems and networking services together into a synergistic system:

- Need for rapid and robust communications authority between units within the battlefield and rear support resources independent of organization, i.e. direct sensor-to-shooter and joint operations. This is a doctrine issue.
- Extremely varied operational environments dictated by physical phenomena, coalition partners, multiple foreign regulations, and international treaties.
- Need for rapid information dissemination and access.

The Generalized Communications Channel Model, described in Chapter 2, is a starting point for understanding the synergy between radio communications and networking services. In that section, this report argues that future radio systems must be designed for agility within the four feature resource space because of wide, unknown range of possible missions and the uncertainty of RF operating environments. DoD can no longer afford to design and procure radio systems for specific missions, the possible constraints are simply too complex to anticipate.

Given that adaptive communication systems are required, what must be accomplished to deploy these systems? First, the communication components must be designed and implemented in a manner that they can be controlled by an authorized external management sub-system. Second, techniques to set the controls to achieve desired system characteristics and properties must be designed and implemented. Third, instruments and databases must be implemented to sense the local environment and adjust the radio system based on present needs and local rules. Fourth, network protocols must be designed and implemented to ensure the multiple radios are interoperable.

Examples of adaptations the task force anticipates include:

- Change to a different set of RF frequencies to avoid interference, penetrate foliage, gain bandwidth for capacity, communicate with a different information service, avoid detection, et cetera.

- Change modulation/power/compression to increase/decrease capacity, avoid or ignore detection
- Change antenna characters to point/track a new information service, avoid detection, avoid interference, et cetera.

Coordinating these types of changes in timely manner will require robust network communications between radios. For example, if two radios are to change frequency, time, spatial orientation, or coding, both must know the new RF resources to be used ahead of the change and know the exact time of the change. Network protocols to communicate these adaptive uses have yet to be developed.

Many of the technologies necessary to implement the type of adaptive radio system described above are in development.

Software defined radios (SDR), in particular the Joint Tactical Radio System (JTRS), fit this description. SDRs define almost all of their characteristics and capabilities in software modules, which can be quickly switched "on-the-fly" by the user. New capabilities can be implemented by developing and deploying new modules. Modules can easily be selected and controlled by setting parameters.

However, the JTRS program has until recently focused on implementing legacy waveforms. The focus on legacy waveforms, while meeting interoperability needs with existing systems, has not taken full advantage of the SDR concept or capabilities. The wideband networking waveform (WNW), which supports multiple capacities and modulation types, is a first step towards a more flexible radio system.

While SDRs promise extensive flexibility and rapid deployment, development of SDR capabilities should not be underestimated. The software is difficult to develop, testing for feature interaction is complex, and adaptive systems are difficult to test and evaluate. Also, the impact on antenna design is significant based on platform type (i.e., soldier, vehicle, UAV, aircraft).

The DARPA XG program concentrates on sensing RF signals and uses local databases to infer the local RF environment and to exchange information among a set of radios. Research programs at the service and industrial laboratories promise high performance circuits and signal processing capabilities. Adaptive

mobile network routing protocols are under development. However, the task force views these as fragmented efforts that need to be pulled together and coordinated to achieve the presented vision.

A crucial need, and perhaps a show-stopper, is dynamic cryptographic keying of deployed systems. The ability to authenticate a user to allow them to join a network, determine user authorizations, avoid network compromise should a node be lost, and other capabilities are required. Additionally, considerable policy, cost, power, security, and interoperability issues surround a truly user-friendly, mass-deployment cryptographic system for next-generation communications. Assured and robust protocols and techniques are perhaps the least developed technologies required to instantiate adaptive radio communications systems.

There is a critical need for a large-scale integrated simulation capability that gives the information system designer the ability to adapt subsystem parameters and strategies based on a dynamic information model. Using all of the aforementioned advances in technology available on an ad hoc basis, the planner would get the maximum performance out of a heterogeneous network of SDRs. This simulation tool would need to translate directly into operational settings for a deployment. It is not likely that commercial industry would lead the charge, given that most commercial systems will continue to operate with fixed base stations.

TOR ITEM 5: INTERFERENCE

The TOR states: *Wideband RF modulation is a very flexible format that may permit the DoD to fully exploit its variable code length and bandwidth-on-demand characteristics using packet switching techniques to meet the DoD's long-term United States and possessions (US&P) communications requirements. The potential limitations of this approach should be addressed including communication systems that cannot effectively employ direct sequence modulation. The implications of this approach during a transition time when both legacy systems using traditional narrow band techniques and systems using these new technologies also should be addressed. Implications of the employment of Wideband RF modulation for the U.S. regulatory regime should be identified and assessed.*

The promise of wideband RF modulation is that communications can occur at very low power spectral density levels and, hence, the wideband

communications will not interfere with existing communications systems. Unfortunately, no such blanket statement can be made. Our concerns are threefold. First, many existing military systems are designed with very limited noise margins. Any additional interference (noise) would degrade system capabilities. Second, the aggregate effect of multiple low power density emitters on an existing system is not well understood. Third, interference effects on low power spectral density systems by existing narrow-band systems are not well understood.

From these observations, one might conclude that significant additional study is in order. However, those types of studies are expensive, require significant amounts of time, require a large-scale testbed, and additional time necessary to modify the affected systems. The DARPA NetEx program is taking this approach with respect to ultra-wideband systems. While they will compile useful interference results on some two dozen systems, it is unlikely they will be able to state anything about other systems. That is, the results would be static, reflecting the examined systems, and not recently deployed systems or new environments.

The radio communications environment is evolving with new services, architectures, modulation techniques, among many other technologies. Some advocate a complete opening of spectrum resources and encourage that all systems should be (ultra) wideband system. The advocates tend to think that interference can be handled by "smart receivers" that reject interfering signals. It is difficult, in the global market, to determine which might be successful and which will fail. A particular radio communications deployment might encounter new services, a high powered transmitter, or a conjunction of many relatively low powered, spectrum sharing devices. One has to anticipate that the RF environment and/or mission is likely to change rapidly and DoD system must adapt.

In a dynamic system, the following adaptations might take place:

- A receiver senses an interferer and coordinates with its corresponding transmitter to change to a different portion of the RF Resource Space.
- A system senses an interferer affecting the receive function and executes an adaptive interferer cancellation algorithm. The cancellation algorithm might be re-pointing an antenna, steering an antenna null in the direction of the interferer, or use signal processing to subtract the interfering signal.

- A receiver senses an interferer and coordinates with the interferer to change to a different portion of the RF Resource Space.

However, all radio communications comes down to how much signal energy is detected at the receiver, how much interference can be rejected through antennas, filters, and signal processing, and can the desired signal be detected and de-modulated given those receiver energy levels. The extra processing comes with the price of computing resources and power. Further, if a nearby system is transmitting several mega-watts of RF power, signal processing and detection will not help when the physical energy detection mechanism is overloaded. DoD needs to be aware of these emerging ideas and architectures and articulate DoD's requirements and concerns with a technically strong foundation.

TOR ITEM 6: COST AND TECHNICAL RISKS

> The TOR states: *Implications for the cost and technical risk associated with the extensive use of Wideband RF modulation by the DoD should be identified and assessed.*

Both cost and risk become drivers in the quest to fully utilize the available bandwidth and provide the connectivity required for the warfighter of the future.

As DoD communications requirements expand, the task force finds the cost of DoD systems can benefit from the advances in the commercial communications sector. Yet the demands of the DoD can be very specialized (e.g. non-commercial radio frequencies and wider operating ranges), resulting in small parts quantities and performance requirements beyond those of the commercial sector. In many cases, this obviates the opportunity to use commercial capabilities and components. Wherever possible new communications strategies should be designed such that they can capitalize on the technology investment and production base of the commercial sector but, where this does not yield results, investments will be required to minimize risk, reduce cost, and provide the required capability.

The demands made on communications systems by such tasks as intelligence, surveillance, and reconnaissance (ISR) illustrate the drivers for cost and risk. ISR systems generally consume tremendous bandwidth, increasingly require global

connectivity, demand immediate global presence, and require mobile networking. All of this must take place in a congested electromagnetic spectrum space, in all environmental conditions, and under battle conditions.

In addition, the sensor to shooter path is becoming more direct, thus requiring very small units of action to have full access to ISR data. This causes proliferation of systems, requires smaller, less expensive systems to be available, and generates entirely new requirements. In the past, ISR systems were point-to-point, could be elaborate, expensive and power hungry. The new systems must be small, mobile, and power conserving while at the same time delivering the kind of performance provided only by large centralized systems in the past.

In order to realize these systems (and others), the costs and risks need to be fully assessed and plans for mitigating the associated problems must be developed. The task force assessment of the risk items includes the following, non-exhaustive list.

1) Device Technology - Device technology has advanced a great deal in the commercial sector and many current DoD systems have benefited tremendously. In the areas of digital devices, computing and signal processing in particular, the commercial sector is the great enabler of new capability. In some areas where the DoD does or will operate however, there is a need for improvement to enable the development and deployment of significantly improved systems. The two most prominent examples of the need for device technology improvement are solid-state power amplifiers and antennas.

2) Power Amplifiers - For many mobile applications, solid-state power amplifiers are becoming a cost driver and a performance limiter. Current solid-state power amplifiers are highly inefficient, twenty percent efficiency is considered to be state-of-the-art performance at Ku-band today. This means that the devices consume five times as much power as they radiate, eighty percent of the input power must be dissipated as heat, and significant battery energy is wasted. The resulting communications devices are larger and heavier than is desirable.

Further, the power amplifiers and RF front ends which exist today do not lend themselves to the highly flexible frequency plans which this report envisions. In many cases, the limiting factor on the ability to rapidly re-configure a communications system is the ability to readily tune to a new frequency while meeting the power output and frequency mask requirements. Software radios, as

discussed, have tremendous potential for highly agile, adaptive communications, but that capability is moot if the use of the available bandwidth requires a non-realizable RF front end.

3) Antenna technology – In the frequency bands of interest to the military, current antenna systems are still often based on parabolic dishes. This means that they are relatively large, are quite fragile, and are not agile. Research has been going on for years in the area of active antenna arrays and some progress has been made, but these systems are still mostly experimental and are very expensive. There is some correlation of these efforts with the solid-state power amplifier research, since many of the schemes require multiple individually phased power amplifiers. Progress in antenna design and controllable power amplifiers could open new avenues to sharing and exploiting electromagnetic spectrum.

4) Networking Protocols – The source of most of the networking routing protocols, commercial industry, has not adequately addressed messaging protocols for network entry, authentication and authorization in a way that is suitable for long range, variable latency, mobile infrastructure, hostile environments. The existing commercial protocols for wireless networking are designed for short range Ethernet Local Area Networks, such as IEEE 802.11, or cellular telephony based, rather than being IP router based.

For routing protocols once nodes have entered the network, something better than an Open Shortest Path First (OSPF) link state announcement needs to be identified. A method for discovery/definition of link quality that is tied to the physical connection is needed. Current industry protocols assume a high quality physical link and are not designed to quickly identify and react to varying conditions. Military wireless communications must use routing protocols that can account for long distances, high latency and intermittent conditions often found in military/intelligence links.

Existing academic research usually does not concentrate on military style high bandwidth interconnect between networks and therefore may not yield the solutions required for the current and projected DoD problems. Academic research into MANET routing generally assumes a flat network of peers, or a simple two-level hierarchy, with a shared communications channel. This is appropriate for the individual soldier and small unit networks, but does not match a network-centric concept. The theater-wide military networks required for sensor to shooter integration and Network Centric Warfare in general are

more prone to be hierarchal in design with dedicated trunks (wired or wireless) between subnetworks and LANs.

In addition, current routing protocols (such as Mobile IP) and hardware solutions generally assume stationary routers and mobile end users, rather than the mobile router infrastructure with variable network exit and re-entry that characterizes the demanding DoD environment. It is not enough to be able to adapt to small units moving between local routers, the DoD must also account for varying connections and conditions between the routers – for which Mobile IP has no solution.

5) Software Radios. Software radios can be viewed as both a risk and an opportunity. The risk lies in the capability to develop and implement communications protocols, waveforms, etc. that are not supportable by existing device technologies, spectrum allocations, and protocols. This is a complex task requiring detailed planning and diligent software implementation. There is a danger that overly complex network interactions are required as well. The opportunity is that, in the event that highly flexible amplifiers and antennas can be developed, software radios can take full advantage of this technology. Research into software radio algorithms is required to ensure that as Digital Signal Processing (DSP) devices and Field Programmable Gate-Arrays (FPGAs) become faster, larger, and cheaper, the optimum waveform techniques are developed in parallel. New initiatives to place some of the burden for interference management on the receiver also pose risks to existing radios and it is possible that research and development in the area of software radios could mitigate or avoid some of that risk.

The wideband communications technology has several clear cost elements, trends, and correlations which may be used to estimate costs. These include:

- Most of the technology required for modern wideband wireless techniques is predominantly digital and software/firmware; analog circuitry is a constantly shrinking portion of the equipment and development cost.
- As a first-order approximation, the total amount of circuitry and software in a purchased wireless communications device is directly proportional to the data rate; this approximation takes into account digital, RF, analog hardware as well as amortized software/firmware.

- Non-recurring development costs of embedded communications software/firmware will comprise the lion's share of the DoD communications' purchase dollar; as such, the key enabler or deterrent for industry's development of such software/firmware are the accounting rules by which they may recover their non-recurring investment.
- Digital technology continues to increase in capacity and decrease in cost, following the classical Moore's Law time/cost curve.
- Analog circuitry is a very small portion of the total equipment cost, and is mostly implemented in integrated circuits whose cost is quantity-driven, typically requiring production in the millions of units and suggesting that DoD needs can only be met affordably by leveraging commercial technology or budgeting for the steep front end cost of integrated circuits.
- Higher information capacity needs drive users to higher frequencies that can support the bandwidth/data rate. This in turn drives semiconductor process and device technology needs, requiring a constant stream of new materials and finer geometry processes to support the higher frequencies. The result is that there never appears to be an "equilibrium" where a new semiconductor technology for a particular band is allowed to stabilize and mature for years (like silicon and digital circuits); rather, a constant semiconductor investment stream is required and should be planned for.
- The contention for spectrum in higher bands is heavily driven in the commercial sector by the cost of licensing spectrum. Obtaining "pioneer" licenses in "unexplored" portions of the spectrum is inexpensive though risky. In the face of this and the search for higher frequencies for greater capacity, DoD once again is outside the process.
- The extension of this cost basis is rapidly transitioning to the free space optical domain, where very high speed "wireless" [fiberless] optical communications can convey gigabits of data. As yet, this is "pioneering" technology and services, and has no FCC licensing (although they are considering the ramifications but are already behind the power curve). DoD would be well-advised to "stake a claim" in this vital future medium before the ad hoc market rules dominate the medium, causing the potential for significant future costs.

In summary, the costs and risks of moving to a more comprehensive solution to the efficient use of wideband RF systems can best be managed by taking advantage of the relevant developments in the commercial sector, by recognizing the areas where commercial efforts are not applicable, acknowledging important trends in communications systems implementations, and supporting the appropriate research and development required for DoD unique problems.

SUMMARY OF FINDINGS

The cost and complexity of designing and building new network-centric communications systems is significant. Flexible dynamic communications systems that use the entire RF Resource Space are integral to the success of network-centric systems-of-systems. Current investment in new smart communication systems is essential and shows the huge potential improvement in capability and capacity.

However, radio communications systems need to operate in a morass of detailed domestic, international, and doctrinal rules and regulations and pressures from the commercial sectors for new spectrum resources. Future wideband communications systems need to account for and adapt to current, emerging, and future regulations and laws.

The spiral development philosophy allows gradual insertion of these new technologies as they are designed and tested, providing increased performance over time. Diligent attention to how a component fits into the larger system, not just to the component itself, will assure that the end result is a fully integrated and compatible systems-of-systems. The days of independently pursuing a technology and developing a component without considering its role in the encompassing system are gone.

CHAPTER 5: RECOMMENDATIONS

Networks, by their very nature, derive their value from the inter-connectedness and rapid exchange of information. General Richard Myers, Chairman, Joint Chiefs of Staff, captured the importance of combining talents of many different military units when speaking to Pentagon workers in November 2002.

> *"In my travel to see the war fighters around the world, no single unit ever seems to be able to do the job all by itself and do –it – and do it alone. The best tactical solutions are often found when we combine the talents of many different units and many different services. Those operations, the successful ones, are often characterized by a climate of trust and confidence between the senior leadership. We need to learn from them, and we need to continue to improve our joint war fighting. Whether you're a soldier, a sailor, airman, Marine, Coast Guardsman, or DOD civilian, this war on terrorism will require great innovation and sacrifice on all our parts over the next several years."*
>
> *– General Richard B. Myers, Chairman, Joint Chiefs of Staff, November 12, 2002, Pentagon Town Hall Meeting*

In a similar vein, network-centric warfare demands the combined capabilities of a range of technologies: antennas, RF circuits, signal processing, resource management, network routing, and network services. Putting a collection of world-class technologies together without taking into account how they interact and even forcing them to interact without due consideration is doomed to failure.

Following are the recommendations of this task force. Several of the recommendations include specific technical or programmatic implementation objectives.

AGILE WIDEBAND COMMUNICATIONS SYSTEM INITIATIVE

RECOMMENDATION #1: THE OFFICE OF SECRETARY OF DEFENSE MUST INITIATE A COMPREHENSIVE PROGRAM IN AGILE WIDEBAND COMMUNICATIONS SYSTEMS.

Agile wideband communications systems are capable of addressing all of the Department of Defense radio frequency communication needs. They offer high data rate transmission, ability to meet all possible military requirements, such as covert communications and robust communications, and provide the capability to adapt to the local/regional communications environment. The DoD Science and Technology community has recognized the need for basic science and project development in wideband technologies. The service laboratories also recognize this need. However, the DoD lacks a comprehensive program to guide, implement, and deploy the crucial wideband technologies.

A comprehensive program should coordinate research and development programs across DoD research organizations; invest in extensive experiments, evaluation, and integration in a ongoing testbed; organize a network centric architecture office to define and continuously update a roadmap for investment, integration, and deployment; and use the advanced technology and experience to lead and formulate future spectrum policy at the national and international forums.

RF COMMUNICATIONS SYSTEMS RESEARCH AND DEVELOPMENT

RECOMMENDATION #2: ASDNII AND USDATL SHOULD INCREASE AND FOCUS INVESTMENT IN FLEXIBLE AND ADAPTIVE AGILE WIDEBAND COMMUNICATIONS TECHNOLOGIES TO ACHIEVE NECESSARY MISSION CAPABILITIES IN A HIGHLY DYNAMIC RADIO FREQUENCY COMMUNICATIONS ENVIRONMENT.

It is clear from this study that every aspect, every technology in an RF radio communications system should be programmable and controllable. That is to say, the wireless communications function should – and will in

the future - simply be an embedded component of a user subsystem and the radio as a standalone procurable item will cease to exist. More important than control within a component, e.g. a smart antenna or tunable receiver, is that the component be controllable from another system component. For example, smart antenna designers must expect their antenna will be controlled from a network resource manager and network traffic routing will be controlled from network services sources and sinks. This implies the flexible capability must be built-in and the interface well defined and available to other parts of the system. A significant part of the investment should be in the required flexibility and the interfaces (the protocols) between components. Every program manager, every principle investigator should be challenged to answer how their investment fits in the larger RF communications systems picture. Specifically,

- Director, Defense Research and Engineering (DDR&E) should continue research and development in breakthrough RF device and circuits, antenna, signal processing, software radios, and networking technologies at the science and technology organizations, the service laboratories, and engineering research and development centers.
- DDR&E and NII should make a significant investment in network management and access technologies for mobile, ad hoc, military tactical networks. Of particular importance is investment in research and development of flexible and adaptive RF communications systems, RF link protection such as low probability of detection/intercept (LPI/LPD), mechanisms for robust and secure mobile infrastructure, inter-connected and inter-operating communications systems, and the necessary control mechanisms and protocols.
- DDR&E should increase investment research and development in dynamic, efficient, ad hoc, adaptive spectrum utilization procedures and services and automatic spectrum management necessary for anytime/anywhere missions.

Specific technical objectives should include:

- Show the feasibility of at least one instantaneously wideband waveform capable of simultaneous operation in non-contiguous bands;
- Perform experiments proving that communications using time-variable spectrum occupancy at a level more sophisticated that frequency hopping technology is feasible;
- Demonstrate wideband codes assigned to a "large" set of users within a subnet, with subsequent modification of the assignment due to introduction of new users and/or change in demand by one or more nodes, control may be centralized or distributed, as dictated by other aspects of the architecture;
- Show at least one architecture and a related set of protocols that permit network operations to be conducted by DSSS signaling in an orderly fashion and allow users the desired connectivity and data rates;
- Show that adequate time and frequency control can be maintained within subnets, and perhaps at higher tiers as well. This involves algorithms for arrival time measurement at the various nodes and determination of subsequent transmission times. The goal should be to achieve isolation 10-20 dB better than would be expected in an uncoordinated environment;
- Perform experiments in which operation is conducted within otherwise occupied bands to ascertain that the ambient interference does not compromise the performance of the test system, nor the test system adversely interfere with systems in the "host" band;
- Develop a conflict monitoring capability to determine how well the spectrum access methodology performs and to generate corrective data for subsequent refinement of the spectrum access strategy and network architecture details; and
- Develop a data reduction capability in which the characteristics of the test radio platform(s) are extrapolated to estimate what would be required in a complete system and to determine whether a technology development program for any radio components is needed and what its content might be.

Only through investment in flexible and adaptive RF communications will DoD be able to meet the variety of its missions in the locations necessary.

RF COMMUNICATIONS SYSTEMS TESTBED

RECOMMENDATION #3: ASDNII MUST ESTABLISH AN AGILE WIDEBAND COMMUNICATIONS SYSTEMS TESTBED.

Inherent in building systems is the need to experiment, test, integrate and evaluate the interactions of the numerous components in real-life situations, in the physical environment, and on a continuous basis. A large-scale testbed is needed to assess, evaluate, and transition technologies and capabilities from research and development into production and deployment. Such a testbed would provide feedback to the research community and identify as soon as possible problems in anticipated solutions. The testbed could be used to try new algorithms, for example new waveforms on a JTRS radio network or new routing algorithms for network services, without significant additional investment by individual projects in hardware and logistics.

Further, the testbed would be used to measure and evaluation interference between existing defense, government, and commercial systems and emerging wideband systems. Solid measurement data is necessary to understand system interactions and to provide a basis for policy recommendations when working with regulatory agencies and the commercial and international sectors.

The testbed should be built in cooperation with the commercial sector to explore new RF communications technologies and determine interference, compatibility, and performance characteristics of new radios. The testbed should be used to evaluate the effectiveness of spectrum management tools and techniques.

Testbed objectives include:

- Performance of new equipment, algorithms and software should be verified in simulation and laboratory test bed settings prior to field trials. A laboratory testbed should be funded by DDR&E to develop the facilities, equipment, software suites and personnel needed to carry out the responsibilities of functional testing of equipment and software as an integral part of an overall program to develop the integrated network capabilities.
- Research a next generation JTRS waveforms to address current limitations. Potential enhancements include integration of Space-Time processing (MIMO), improved mobile networking protocols, integration of XG-like adaptive spectrum access, reduction in overhead associated with current networking protocols, additional modulation options (in addition to the 4 current ones), and development of networking protocols and modulations suitable for use at higher frequencies (current upper limit is 2 GHz).
- The potential application of CDMA technology (orthogonal codes) and precision timing to radar systems to decrease spectrum use and increase frequency reuse should be studied and demonstrated through DDR&E sponsored research programs.
- Conduct research into the application of adaptive spectrum access protocols to the problem of mitigating the near-far problem in CDMA systems.
- Electromagnetic compatibility (EMC) analysis of wideband waveforms versus legacy equipment and a review of DoD spectrum use to migrate or replace spectrum-inefficient equipment. There should also be an analysis/modeling of dynamic spectrum access techniques (e.g., DARPA XG Program) for EMC affects on RF equipment environments.
- A modeling and simulation test bed should be developed to evaluate wideband, networked, adaptive communications systems and the effects to and from RF equipment environments. The Joint Spectrum Center (JSC) should be an active participant in each of these activities.

IDENTIFY AN OFFICE FOR NETWORK-CENTRIC COMMUNICATIONS ARCHITECTURE

RECOMMENDATION #4: ASDNII SHOULD IDENTIFY AN OFFICE FOR NETWORK CENTRIC COMMUNICATIONS AND DEVELOP A ROADMAP FOR TECHNOLOGY INVESTMENT, EVALUATION, AND TRANSITION INTO OPERATIONAL SYSTEMS. THE ROADMAP SHOULD INDICATE PHASE-IN AND PHASE-OUT OF TECHNOLOGIES AND ARCHITECTURES.

ASDNII must identify an office for network-centric architecture. This office would articulate how one goes about building a network-centric communications system. The various Joint Vision documents call for "network-centric warfare," "information superiority," and other capabilities built upon communications. However, these documents do not elicit how such a system might be built, nor the components necessary to build such a system. This leaves the door open to many claiming they are working toward a network-centric system without have to explain exactly how their work fits into the system.

To aid ASDNII decision process, the Network-Centric Architecture Office (NCAO) should develop an RF communications/network management technology roadmap. The roadmap should serve two purposes: a strategic plan and a tactical plan. The strategic plan should be driven by the requirements and needs of the services. It should show the components actually needed to build a network-centric communications system, including digital and analog hardware as well as software/firmware, the time those components are likely to be available, and identify technology challenges to be solved to achieve the desired result. The tactical plan should show the prototyping and development steps needed to move wideband technology from the laboratory to deployment and use. The roadmap should be updated on a semi-annual or annual basis as technology and systems evolve. DoD, federal government, industry, and academic participation in developing and maintaining the roadmap is essential.

Without such a roadmap, every technology that might fit into a network-centric RF radio frequency communications system becomes a

candidate for investment. Without clear articulation of how the technology contributes to the network-centric system, funding is likely to be misdirected. The roadmap should not be a gatekeeper to early research investment in innovative technologies, doing so would limit the very innovation that is relied upon.

Specific Recommendations of the task force are:

- ASDNII should identify Network Centric Architecture Office (NCAO) chartered with integrating diverse DoD efforts to provide technical alternatives to the current form of radio communications and network management. The goal is to develop an insertion path for new technologies that can be explained to Congress and to the American people as a cornerstone of DoD's leadership of the public trust in this area. The NCAO should be consolidated from ongoing NII, JTRS JPO and DDR&E wireless networking technology efforts and be placed under central management. The NCAO would be responsible for coordinating research, development, experimentations, and evaluation related recommendations of this report.
  - The NCAO office should develop a roadmap for technology investment, evaluation, and transition into operational systems. The roadmap should indicate phase-in and phase-out of technologies and architectures and be sufficiently specific to permit the development of implementation and transition plans by all unified Commands, Services, and DoD agencies. The roadmap should indicate when to reallocate or 're-mine' spectrum as obsolete military inventory is removed from service.
  - The NCAO should develop executable plans for wideband technology pilot programs. Where possible, these technology pilot proposals should demonstrate Joint service application. Plans should include service sponsorship commitments to enable submission as ACTDs, ATDs, or insertion into Joint Experimentation.

- The NCAO should draft a report recommending an executable detailed study to establish a cohesive, well-focused science and technology program to enable capabilities in wireless networking technologies. The detailed study will quantify capability improvements possible in each of the following areas: communications, surveillance, targeting and weapons delivery. The study would include detailed numerical analyses and conclusions regarding the effect of improved spectrum.

- ASDNII should establish a senior technical advisory board comprised of industry and government scientists for innovative use of network and spectrum technologies. The advisory group should consist of recognized industry experts in inter-networking technologies, commercial information and network security technologies, emerging information transfer technologies and systems, and other commercial activities such as standards development, infrastructure development, and the like. The advisory board would monitor the network-centric roadmap, suggest modifications, and alert DoD to emerging technologies and policies. The advisory board could be set up under the auspices of the National Research Council similar to the Board on Army Science and Technology.

- ASDNII with the NCAO should work with the service representatives responsible for requirements generation to identify anticipated shortfalls in achieving JV2020 capabilities that could be addressed by wideband systems. For those potential wideband applications, a high level CONOPS will be prepared to help identify specific wideband system capabilities to be addressed through DDR&E sponsored research.

- Proposals in this report represent a fundamentally different approach to using the RF resource space. NII, Joint Staff, and service representatives should identify compatibility and interoperability issues associated with a migration to wideband systems and develop a DoD-wide transition plan.

The Network-Centric Architecture Office would in many respects carryout the systems engineering work for a network-centric

communications system. It would insure the wide range of mission requirements and capabilities are met, that components work together through the testbed, and anticipate future needs and requirements.

POLICY

RECOMMENDATION # 5: ASDNII MUST TAKE THE LEAD IN DEMONSTRATING STEWARDSHIP OF ALLOCATED SPECTRUM AND THE ADVANTAGES OF AGILE WIDEBAND RF COMMUNICATIONS TO DEVELOP AND PUT FORTH SPECTRUM POLICIES BASED ON EXPERIENCE.

A common view is that the Department of Defense controls a significant portion of the radio frequency spectrum, but a recent General Accounting Office report [GAO2002] showed that the federal government has exclusive access to only 13.7% of the spectrum between 9 kHz and 3.1 GHz compared to 30.6% exclusive access to that same spectrum by the non-federal community. Given the demand for new commercial wireless services, the mission requirements of the DoD and the current lack of a national spectrum policy, the DoD will need to work within its current allocations in the foreseeable future.

Any review of spectrum policy should be aimed at promoting efficient use of the spectrum in a way that best meets the demands of federal and non-federal users. As both DoD and the private sector employ advanced communications systems capable of transmitting greater amounts of data, the spectrum requirements of both are increasing. Certain systems, such as wide area mobile operations must be accommodated in bands below roughly 4-5 GHz to achieve reasonable coverage. Policies should focus on means of making this prime spectrum available for services that require it, such as wide-area mobile. The process should examine ways to maximize the efficiency use by grouping like services together in order to minimize interference, and it should provide a well-defined technical structure. Services such as fixed services or services that serve small areas should be accommodated in higher bands that are not technically suitable for wide area mobile services.

In general, it will not be possible for military and commercial systems to be deployed in the same area using the same frequencies without causing harmful interference. However, ASDNII could explore ways for systems to be deployed on a coordinated basis to the mutual benefit of all users. To a large extent, commercial and military use occurs in different geographic areas. Accordingly, it should be possible to divide use of spectrum on a geographic basis for similar systems. Agreements could be reached between commercial licensees and DoD to have some shared spectrum and for DoD to have priority use of the otherwise commercial part of the shared spectrum during a national emergency. There is precedence for agreements that would provide for DoD control of the commercial infrastructure if necessary.

Consistent with the need to group like services, a focused U.S. spectrum management effort to provide additional spectrum for wideband, wide area services could put the United States in a leadership position to set the direction for global harmonization of spectrum. Harmonization would benefit both the military and the commercial sectors by providing global markets and consistency in spectrum availability for the military. Greater global harmonization would help drive down the cost of equipment and services.

DoD investment in wideband technologies could significantly enhance commercial usage of the technology. It is possible that agreements could be reached that would result in increased and more efficient sharing between military and commercial services. To the extent that the military and/or homeland security is authorized to have priority over other uses during an emergency, a commercial infrastructure based on wideband technology would be beneficial.

ASDNII must take a number of steps to demonstrate leadership in spectrum management. These steps include:

- Pursue an active agile wideband program to have the tools for future spectrum management;
- Reduce/eliminate the assignment of narrowband frequency channels in selected bands and utilize agile wideband

technologies and dynamic RF resource management to increase utilization and capacity within the selected bands;

- Used agile wideband systems to demonstrate improved spectrum utilization and dynamic spectrum management within DoD allocations in experimental, test, and evaluation programs;
- Take the lead in developing standards, through established forums (e.g. ITU, FCC, NTIA, standards bodies), for dynamic spectrum management and increased RF resource management; and
- Use experience in agile wideband radio systems to develop a strategy for balancing national security and economic needs for spectrum and recommendations for spectrum management policies and techniques. The strategy and recommendations should address domestic, international, and coalition (e.g. NATO) issues. Recommendations should be presented to the appropriate leadership and national and international organizations.

CHAPTER 6: CONCLUSIONS

Radio communications is currently one of the most exciting technologies in research and development. Breakthrough technologies in devices, circuits, antennas, signal processing, and mobile networking offer immense capabilities for communications. But as these individual technologies advance, the synergy of linking these wide ranging technologies is also being experienced. Smart antennas linked to agile radios controlled through a decentralized network manager offer increased mission critical capabilities and resource utilization. This is a shift in focus from limited, single use communications systems to network-centric, system-organized capabilities.

The innovation present in radio communications research indicates no single technology will satisfy all missions. Ultra-wideband systems promise useful sharing and sensing capabilities, but also are limit in distance and are likely to cause interference with crucial existing services. CDMA offers significant robust capabilities in point-to-point and fixed infrastructure applications, but in a peer-to-peer networking application, the same capabilities may be difficult to achieve. Further, the need for contiguous spectrum in direct-sequence CDMA may make it difficult to operate in some jurisdictions. A significant investment in direct-sequence CDMA is risky at this time given the lack of experience in peer-to-peer radio networks and worldwide spectrum allocation problems.

Agility, robustness, networking and adaptation, along with traditional properties of anti-jam, low probability of intercept, capacity, foliage penetration among others, will be crucial properties for the military in the future. These emerging properties require more than just linking multiple systems together with a single protocol, e.g. the Internet Protocol, but require the development and evaluation of system-wide management and control mechanisms. Given the complexity of these multiple communications systems, it is absolutely necessary to evolve these systems over time through extensive experimentation and evaluations. Analysis, simulation, and emulation, while important, are not sufficient to develop reliable communications systems.

It is through demonstration and action that the Department of Defense can take the lead in offering new radio communications technologies and new strategies and policies to the larger national and international communities.

Demonstration of agile radios, dynamic spectrum management, and high RF resource utilization can be the driving force behind increased capacity for both DoD and the commercial sector and provide the basis for introduction of new wireless services.

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APPENDIX A. TERMS OF REFERENCE

THE UNDER SECRETARY OF DEFENSE

3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

ACQUISITION,
TECHNOLOGY
AND LOGISTICS

28 MAY 2002

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference -- Defense Science Board Task Force on Wideband RadioFrequency (RF) Systems

You are requested to form a Defense Science Board (DSB) Task Force to review and advise on key aspects of the policy and technology issues associated with the military applications of wideband Radiofrequency systems. The Department of Defense is facing increased competition with civil sector users for the radio frequency spectrum. The civil sector demand for mobile telephony and data services has dramatically increased the need for access to an increasing share of the spectrum. The allocation of the RF spectrum to potential users is not strictly a national decision. Rather, such decisions are made in the context of a resource shared on an international basis. At the forthcoming (2003) World Radio Conference (WRC) in Caracas, Member States of the International Telecommunication Union (ITU) will seek to reach agreement with respect to uses of radio spectrum that cross national borders, The outcome of this conference will have an important effect, as a practical and policy matter, on the ability of the US government in general, and the Department of Defense, in particular to make sufficient spectrum available in the United States to support the needs of multiple potential users of spectrum and will have a significant impact on DoD systems' access to spectrum outside of the United States.

Alternative concepts permit more efficient use of the RF spectrum. Among these are modulation techniques that permit multiple users to simultaneously share RF spectrum without subjecting users to mutual interference. Wideband RF modulation, such as wideband CDMA or ultrawideband, offers the potential to permit multiple users to share the same RF spectrum without mutual interference. Its successful employment for military applications could significantly diminish military requirements for the elusive use of portions of the RF spectrum thereby allowing both civil and defense sector users to share the same portions of the spectrum. Neither the US domestic regulatory regime nor the treaty and recommendatory mechanisms of the ITU have yet adequately addressed use of such systems.

The Task Force should support the immediate technology assessment needs of the Assistant Secretary of Defense (C3I) in both his DoD and interagency role. Initially, the task force is to examine six areas.

1. The Task Force will identify the technical issues associated with the employment of Wideband RF modulation by the Department of Defense and defense-related agencies and its potential impact on other defense and non-defense users of the RF spectrum. In particular, the implications of DoD use of Wideband RF modulation as an alternative to a requirement for additional RF spectrum allocation(s) for the DoD should be assessed.

2. The review of the technical issues associated with the employment of Wideband RF modulation by defense related agencies should take account of the concurrent interagency review of spectrum requirements for advanced wireless mobile services led by the National Telecommunications and Information Administration and the Federal Communications Commission.

3. Implications of the employment of Wideband RF modulation for US positions at the future WRCs should be identified and assessed.

4. The technical impact of the DoD employment of Wideband RF modulation on future mobile wireless networking and other users of the RF spectrum should be identified and assessed.

5. Wideband RF modulation is a very flexible format that may permit the DoD to fully exploit its variable code length and bandwidth-on-demand characteristics using packet switching techniques to meet the DoD's long-term United States and possessions (US&P) communications requirements. The potential limitations of this approach should be addressed including communication systems that cannot effectively employ direct sequence modulation. The implications of this approach during a transition time when both legacy systems using traditional narrow band techniques and systems using these new technologies also should be addressed. Implications of the employment of Wideband RF modulation for the US regulatory regime should be identified and assessed.

6. Implications for the cost and technical risk associated with the extensive use of Wideband RF modulation by the DoD should be identified and assessed.

The task force should provide a final report in December 2002. This Task Force will be co-sponsored by me as the USD (AT&L) and the Assistant Secretary for Command, Control, Communications and Intelligence (ASD/C3I). Dr. Gary Minden will serve as chairmen of the Task Force. Mr. Bennett Hart, from the Office of the Under Secretary of the Air Force, will serve as Executive Secretary. LtCol Roger W. Basl, USAF, will serve as the Defense Science Board Representative. The Task Force shall have access to classified information needed to develop its assessment and recommendations.

The Task Force will operate in accordance with the provisions of P.L. 92-463, the "Federal Advisory Committee Act" and DoD Directive 5105.4, the "DoD Federal Advisory Committee Management Program." It is not anticipated that this Task Force will need to go into any "particular matters" within the meaning of section 208 of Title 18, U.S. Code, nor will it cause any member to be placed in the position of acting as a procurement official.

E.C. Aldridge, Jr

APPENDIX B. TASK FORCE MEMBERSHIP

Chairman

Dr. Gary Minden	University of Kansas

Task Force Members

Dr. William Ballhaus	The Aerospace Corporation
Mr. Kent Erickson	L3
Mr. Klein Gilhousen	Qualcomm
Dr. Jim Isaacs	ITT
Ms. Diana Johnson	The Aerospace Corporation
Ambassador Travis Marshall	Private Consultant
Dr. Joseph Mitola III	MITRE
Mr. Walt Morrow	MIT Lincoln Lab
Mr. Rocky Roccanova	TRW
Dr. Robert Scholtz	University of Southern California
Dr. K. Sam Shanmugan	University of Kansas
Mr. Robert Sternowski	Rockwell Collins, Inc.

Executive Secretary

Mr. Mark Norton	OASDNII

DSB Representative

LtCol Roger Basl, USAF	DSB Secretariat

Government Advisors

Mr. Joe Capps	Army CIO/G-6
Mr. Scott Hoschar	CNO/OPNAV
Mr. Joesph Inserra	CECOM
Dr. John Knab	DISA
Dr. Alan Lindsey	AFRL/IFGC

COL Danny Price	OASDNII
Mr. David Townsend	NRL
Mr. Owen Wormser	OASDNII

Staff

Ms. Stacie Smith	Strategic Analysis, Inc.

APPENDIX C. LIST OF BRIEFINGS

June 3-4, 2002

Mr. Owen Wormser and Dr. Boudri Younes	ASDNII Topics
Dr. John Gowens and Dr. Brian Sadler	ARL R&D
Dr. Pete Camana	ViaSAT
Ms. Ginger Lew and Dr. Kalle Konstan	ASB Wireless Study
Dr. Dan Scheresko	Space Communications Architecture
COL Steve McLaird and COL Mike Cox	JTRS
Dr. Bob Fontana	UWB Topics

June 24-25, 2002

Dr. Tom Meyer	DARPA ATO Programs
Dr. Steve Huffman	MITRE Briefing
Mr. John Stenbit	ASDNII Directives
Mr. Joseph Inserra	Wideband Radio Systems Technology for Army Applications
Mr. Bob Sternowski	Rockwell Collins UWB
Dr. Klein Gilhausen	CDMA Technologies
Dr. Donald Kelly	UWB and Time Domain Presentation
Maj Dave McMorries	USMC Requirements
Dr. Bobby Junker and Mr. Dennis McGregor	ONR Issues

July 25-26, 2002

Mr. James Sterbenz	MANET
Dr. Gerald Maguire	Telecom Issues
Mr. Byron Barker and Mr. Richard Larson	Defense Spectrum Office
Dr. Alan Lindsey and Dr. Mark Linderman	AFRL Issues
Mr. Paul Perkowski	MILSATCOM Requirements
Col Brian Robinson	Transformational Communications System

August 28-29, 2002

Mr. John Wehling	TRW Topics
Mr. Alex Pidwerbetsky	BLAST and Lucent Technologies
Mr. Ken Pramik	NSA Security Issues
Mr. Jim Marshall	Wideband Analytical Foundations and Demo Recommendations
Mr. Charles Niessen	Spectrum and CDMA Issues
Mr. Kent Erickson	Wideband CDMA and L-3
Dr. Rich Orr	CDMA Network Architecture Implications
Mr. Rob Calderbank, Mr. Suhas Diggavi, and Mr. Naofal Al-Dahir	AT&T Presentation
Dr. Randy Young	Scale Time Offset Modulation

September 26-27, 2002

Dr. Paul Kolodzy	FCC Spectrum Issues
Mr. Scott Harris, Mr. Peter Pitsch and Mr. Jeff Campbell	Spectrum Policy Issues - An Industry Perspective
Dr. Greg Gibbons	Covert Localization and Tracking

October 21-22, 2002

Mr. Mike Mearns	Overview of Navy Developmental Wideband Radars
Mr. Tom D'Amico	Motorola Presentation
Mr. Don Latham	DSB 2002 Summer Study Briefing
Dr. Wolfgang Kober	CDMA Co-Channel Interference Mitigation

November 21-22, 2002

Mr. Paul Roosa	NTIA
Mr. Mike Francl	CDL Briefing
Ambassador David Gross	Department of State Presentation
Mr. Joseph Inserra	Army Action Item

APPENDIX D. GLOSSARY

AJ	Anti-Jamming
AFRL	Air Force Research Laboratory
AM	Amplitude Modulation
ARL	Army Research Laboratory
ASB	Army Science Board
ASDNII	Assistant Secretary of Defense for Network Information and Integration
ATO	Advanced Technology Office (DARPA)
BER	Bit Error Rate
BLAST	Bell Labs Layered Space-Time System
C3I	Command, Control, Communication & Intelligence
CDMA	Code Division Multiple Access
CIP	Communication and Information Policy
CONUS	Continental United States
CSMA	Carrier-Sense Multiple Access
DARPA	Defense Advanced Research Projects Agency
DASD	Deputy Assistant Secretary of Defense
DC	Direct Current
DISA	Defense Information Systems Agency
DoD	Department of Defense

DSB	Defense Science Board
DSO	Defense Spectrum Office
DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
Eb/No	Bit Energy to Noise Ratio
EHF	Extremely High Frequency
EIRP	Equivalent Isotropic Radiated Power
ERP	Effective Radiated Power
E3	Electromagnetic Environmental Effects
FCC	Federal Communication Commission
FDMA	Frequency-Division Multiple Access
FHSS	Frequency Hopping Spread System
FM	Frequency Modulation
FPGA	Field Programmable Gate-Array
FSL	Free Space Loss
GAO	General Accounting Office
GHz	Gigahertz
GPS	Global Positioning System
HDR	High Dose Rate
HF	High Frequency
IEEE	Institute of Electrical & Electronics Engineers
IP	Internet Protocol

IRAC	Interagency Radio Advisory Committee
ISM	Industrial, Scientific, Medical Band
ISR	Intelligence, Surveillance, and Reconnaissance
ITU	International Telecommunication Union
JTRS	Joint Tactical Radio System
kHz	Kilohertz
LAN	Local Area Network
LOS	Line of Sight
LPD	Low Probability of Detection
LPI	Low Probability of Intercept
MANET	Mobile Ad-Hoc Networking
MHz	Megahertz
MIMO	Multiple Input/Multiple Output
NATO	North Atlantic Treaty Organization
NETEX	NETworking in Extreme (DARPA Program)
NLOS	Non line of sight
NTIA	National Telecommunications and Information Administration
OCDMA	Orthogonal Code Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OSPF	Open Shortest Path First

PN	Pseudonoise
QAM	Quadrature Amplitude Modulation
QDR	Quadrennial Defense Review
QDMA	Quadrature-Division Multiple Access
RF	Radio Frequency
RTP	Real-Time Protocol
SDMA	Space-Division Multiple Access
SDR	Software Defined Ratios
SIR	Signal to in-band interference
SPTF	Spectrum Policy Task Force
SS	Spread Spectrum
STEP	Space Time Processing Program
TCP	Transmission Control Protocol
TDMA	Time Division/Demand Multiple Access
THSS	Time Hopping Spread Spectrum
TOR	Terms of Reference
Tx/Rx	Transmitter/Receiver
UAV	Unmanned Aerial Vehicle
UDP	User Diagram Protocol
UFZ	Ultra-Wideband Friendly Zone
UHF	Ultra High Frequency
US&P	United States & Possessions

UWB	Ultra-Wideband
VHF	Very High Frequency
W-CDMA	Wideband-Code Division Multiple Access
WRC	World Radio-Communication Conference
XG	next Generation (DARPA Program)